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Report SIT-DL-81-9-2225
August 1981

SUMMARY REPORT: DESIGN AND DEVELOPMENT OF U-TUBE STABILIZER TANKS FOR THE UNITED STATES COAST GUARD DUAL DRAFT ICEBREAKER

Prepared by:

T.L. Thorsen
(Ship Research Incorporated)

and

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Prepared for:

United States Coast Guard (G-ENE-5D)

under

Office of Naval Research

Contract N00014-80-C-0789
(Davidson Laboratory Project 4853/093-094)

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The objective of the present work was to design and test a U-tube passive roll stabilizer tank for the United States Coast Guard Dual Draft Icebreaker. The purpose of the present document is to incorporate under one cover the several task reports produced in this work by Davidson Laboratory and Ship Research Incorporated, and to provide a brief summary. Owing to the early and intelligent allocation of space in the ship, the stabilizer as designed appears virtually optimum.

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Approved:
Daniel Savitsky
Deputy Director

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INTRODUCTION

The objective of the present work was to design in accordance with normal practice, and test a U-tube passive roll stabilizer tank for the United States Coast Guard Dual Draft Icebreaker. In order to carry out the work the co-operation of two organizations was required: Ship Research Incorporated of Kensington, California, and Davidson Laboratory. It was convenient contractually to have Davidson Laboratory act as prime contractor and Ship Research Incorporated as sub-contractor. To a great extent the contributions of each of the parties were separable as far as reporting was concerned, and thus the technical work naturally became a series of related documents. The purpose of the present report is simply to collect these various documents under one cover and provide a summary of the work.

DESIGN AND DEVELOPMENT TASKS

The present design and development of the stabilizer was separated into six tasks:

1. Preliminary Design
2. Bench Tests of the U-Tube Stabilizer
3. Ship Model Tests
4. Analysis of Results
5. Provide Tank Operating Manual
6. Final Design Drawing

OVERVIEW

Task 1, Preliminary Design

Appendix A is the preliminary design report prepared by Ship Research Incorporated. The preliminary design of a stabilizer usually consists of the following steps. Late in the design process, the ship designer or owner realizes that a roll stabilization system is needed. The stabilizer designer then negotiates with the ship designer for possible locations of the stabilizer on the ship. In each of these locations, a candidate stabilizer configuration is designed to minimize the roll motions of the ship. The candidate configurations are evaluated in terms of roll reductions achieved, weight of water required, loss of ship stability, and impact on arrangements and ship structure. The ship designer and/or owner then select(s) the configuration which represents the best compromise of all of these factors.

In the case of the Dual Draft Icebreaker, in contrast to the usual process, space was allocated to the roll stabilizer very early in the design process in a way which virtually guaranteed good performance of the stabilizer. The stabilizer is located very high on the ship, approximately amidships, an optimum location. The free surface loss is sufficient for good stabilization, and the volume allocated to the crossover duct has allowed optimization of the tank dynamics.

The preliminary design thus consisted simply of identifying the optimum stabilizer dynamics, characterized by the resonant period, and defining refinements in the geometry to achieve the desired dynamics. Four specific configurations were recommended. Each of these configurations represented only a slight refinement of the configuration defined by the space allocated for the stabilizer. The preliminary design report, Appendix A, included the recommendation to minimize structural members inside the crossover duct.

The Coast Guard selected the stabilizer which conformed precisely to the original space allocated to the stabilizer. The Coast Guard at that time opted to locate 6" x 4" stiffeners longitudinally on the underside of the top of the crossover duct, in order to avoid losing headroom in the space above.

<u>Task 2, Bench Tests of the U-Tube Stabilizer</u>

After the stabilizer configuration was defined, a scale model of the stabilizer was tested. A detailed plexiglass model was built to scale of 1:16. Structural members in the crossover duct were modeled accurately. Structure in the wing tanks was not included, since by reasonably careful design this structure will not affect the stabilizer performance.

Extinction tests were conducted to determine the dynamic characteristics of the stabilizer. The tests consisted of initially changing the angle of the water in the tank, setting the tank at rest, then releasing the water by opening a valve in the air crossover duct. The time history of the water motion was recorded. A computer anlaysis of the data produced the resonant period of the stabilizer, the linear damping coefficient, and the quadratic damping coefficient. This work is documented in Appendix C.

Task 3, Ship Model Tests

Shortly after the bench tests of the stabilizer were completed, a model of the ship was tested in waves. These tests are described in Appendix B. The 1:48 model was tested unstabilized with the U-tube stabilizer and with a free surface type stabilizer. The internal geometry of the small scale U-tube stabilizer was adjusted so that the amplitudes measured in an extinction test matched as nearly as possible those measured in the larger scale bench tests.

During the testing it became apparent that the performance of the U-tube would be improved if the damping were reduced and the period shortened somewhat. It was noted that removal of the structure in the duct could be simulated approximately by removing some of the obstructions in the crossover duct of the U-tube tank model. During the large scale bench tests, the resonant period of a configuration with minimal structure in the crossover duct had been observed to be about 10.7 seconds. A small scale configuration, which had approximately this period and which appeared to represent (on the basis of all of the tests leading up to the small scale configuration) the case of no structure in the crossover duct, was installed in the ship model and tested in waves. The performance of the stabilizer was indeed improved by this change. Among the findings of the model test work was also a recommendation for reducing the amount of structure in the crossover duct.

Task 4, Analysis of Results

The Coast Guard, after reviewing other aspects of the ship design, decided to remove almost all of the structure from inside the crossover duct. The modified design includes a transverse floor athwartship the length of the duct at frame 134 and a small amount of structure at the entrances to the duct. Ship Research Incorporated used semi-empirical theory and a crude bench test to estimate the effects of this change on the dynamic characteristics of the stabilizer, and simulated the performance of the final design configuration of the stabilizer for a variety of ship loading conditions and operating environments. These calculations are described in detail in Appendix D.

In addition, several design details were specified including the size and location of the air crossover pipe, the filling system and the emergency dumping system

Task 5, Provide Tank Operating Manual

Under normal commercial circumstances the tank operating manual is completed only after the final locations of vents, overflows, valves, etc., are finally established. In the present instance this could not be carried out within contractual time limits, and accordingly a prototype operating manual was prepared with blanks where specific locations are required. Appendix E contains this prototype document.

Task 6, Provide Final Design Drawing

Ship Research Incorporated Drawing CG80-1 of 5 August 1981 ("Stabilizer Tank for the United States Coast Guard") was prepared to include as much detail as was possible at the stage of ship design then existing. Prints and sepia of this drawing were transmitted direct to the Coast Guard Design Group 6 August 1981. A vastly reduced scale version of this drawing is included as Appendix F.

CONCLUDING REMARKS

The U-tube stabilizer as designed is virtually optimum for this ship. The roll reductions achieved are in the range of 50 to 60 percent at cruise speed in realistic short-crested seas. Much higher reductions may be achieved in swells. The excellent performance of the stabilizer may be attributed to the intelligent allocation of adequate space for the stabilizer at an ideal location on the ship early in the preliminary design process.

The present design has been made under the assumption that the working fluid would be water (fresh, salt, or fresh plus anti-freeze). The stabilizer would still be effective if diesel oil were used, but several design details related to dumping and venting would have to be changed.

APPENDIX A

"Preliminary Design of a Passive U-Tube
Stabilizer for the United States Coast Guard
Dual Draft Icebreaker"

Ship Research Incorporated Report CG80-1
September 1980

PRELIMINARY DESIGN OF A
PASSIVE U-TUBE STABILIZER
FOR THE
UNITED STATES COAST GUARD
DUAL DRAFT ICEBREAKER

Report Number CG80-1

September 11, 1980

prepared for

Davidson Laboratory
Stevens Institute of Technology
Hoboken, New Jersey

PRELIMINARY DESIGN OF A PASSIVE U-TUBE STABILIZER FOR THE DUAL DRAFT ICEBREAKER

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INTRODUCTION

The preliminary design of a passive U-tube antiroll stabilizer for the Dual Draft Icebreaker (DDI) has been completed.

The preliminary design consists of the following steps. First, the possible locations for the stabilizer are identified. Second, various stabilizer configurations are devised which would fit in these locations. The effectiveness of each stabilizer configuration is determined by calculating the ship roll motions with the stabilizer installed, and comparing these to the roll motions of the unstabilized ship. Other stabilizer characteristics, such as the weight of the contained water and the effect of the stabilizer on the ship static stability, are calculated.

Given all of these data, the ship designer can select the stabilizer configuration which provides the best compromise between the expected roll reductions and the attendant penalties of weight increase, static stability reduction, impact on arrangements, etc.

In this report are presented the results of a parametric analysis of stabilizer characteristics for a single stabilizer location. Stabilizer configurations which will have nearly optimum characteristics are described.

The stabilizer configurations are ranked according to expected performance in roll reduction. All of the stabilizers presented will produce substantial roll reductions. We recommend that the best-performing configuration consistent with other ship design requirements be selected.

DESIGN CONSIDERATIONS

In the design of a passive stabilizer system, several factors are considered. These factors are discussed in the following paragraphs.

1. Operational Requirements. It is required to have excellent stabilization in the primary operating condition and as good stabilization as possible in other operating conditions.

2. Tank Dynamics. For excellent stabilization, an antiroll tank must have several characteristics. The free surface loss due to the tank should be 20 to 35% of the uncorrected GM. For most ships the natural frequency of the tank should be about 5% larger than the ship's roll natural frequency. At this tank natural frequency the roll motion of the ship at roll resonance is minimized. Consequently, for most ships the rolling motions while in transit in a quartering sea are most effectively reduced by this criterion. In any case, the damping of an antiroll tank should be between 20% and 50% critical damping.

3. Tank Location. To avoid excessive yaw coupling, the tank should be located near amidships. To be most effective, the tank should be located high in the ship.

4. Tank Height and Water Level. The internal height of the tank should be sufficient to preclude slamming of the water in the tank against the tank tops when the ship undergoes large motion. This generally requires a tank height-to-beam ratio of about 0.25 or greater. It is optimal to have the water level at about one-half the working height, since this gives the tank its largest roll moment capability.

5. Air Ducts. In most cases it is necessary to provide crossover pipes or ducts to carry the flow of air between the tops of the wing tanks of the U-tube. These pipes must be large enough in cross section to avoid sonic speeds under practical operating conditions. The pipes are connected to the wing tanks slightly below the wing tank tops. This geometry provides a pocket of air above the crossover pipe and thereby cushions any slamming of the water against the tank tops.

6. General Arrangements. In all cases the design of the system is constrained by the available spaces within the ship. Ideally the tank should consume a minimum amount of valuable space within the ship, and should have a minimum impact on ship operations.

7. Static Stability. In no case may the stabilizer reduce the ship's static stability below the required minimum.

SHIP CHARACTERISTICS

Geometry and Loading Conditions

Most of the ship data used in the calculations have been extracted from the preliminary design report, reference 2. Five loading conditions were analyzed. These are:

Eastern Arctic, Full Load
" " , 50% Fuel
Great Lakes, Full Load
" " , 50% Fuel
" " , Burned out

The full load displacement and center of gravity is directly from page 79 of reference 2. The other loadings are derived by reducing the fuel loads only. All other loads are assumed constant. The KG of the fuel is assumed to be constant. The burned out condition is, of course, unrealistic, but represents an extremely low displacement, low GM case. It is assumed that the trim is always zero.

The hydrostatic properties are from page 23 of reference 2. The offsets were taken from the lines drawing, reference 3.

A summary of the ship's characteristics for these loading conditions is presented in Table 1.

Roll Dynamics

The ship roll resonant period is estimated by the following empirical formula:

$$T = 0.4B/\sqrt{GM}$$

where T is the resonant period in seconds
B is the beam
GM is the metacentric height uncorrected for free surface losses

With the information available at the current stage of the design, there is no method for computing roll resonant period which is any more reliable than this empirical formula.

The roll damping ratio is estimated at 0.025 for the case of no forward way, and 0.04 for the case of 12.5 knots forward way. These values have not been computed, but are estimates based on experience with similar hulls. It is important to understand that roll damping is actually quadratic (the roll moment is proportional to roll rate squared), while a damping ratio applies only to linear damping (roll moment proportional to roll rate). In a linearized analysis, the quadratic damping must be represented by an equivalent linear damping, that is, a linear damping that dissipates the same amount of energy as the quadratic damping. The equivalent linear damping increases with increasing ship motions. The linear damping used in this analysis, however, is constant. Therefore, small roll motions may be underpredicted while large roll motions may be overpredicted.

General Arrangements

The general arrangements used in this study, in particular the space allocated to the stabilizer, are from arrangements drawings, reference 4, dated 7/1/80.

SELECTION OF CANDIDATE STABILIZER CONFIGURATIONS

The space provided for the stabilizer in the preliminary design is as follows.

Wing tanks: Frames 127 to 143 (16 feet long)
18 to 28 feet from ℄ (10 feet wide)
01 level upward ($\leq$22 feet high)

Crossover duct: Frames 129 to 141-1/2 (12.5 feet long)
$\pm$18 feet from ℄ (36 feet wide)
01 level to 3 feet above (3 feet high)

The location of the stabilizer is nearly optimum. It is high on the ship, which is very good, and it is nearly amidships, which is nearly optimum. Therefore, there is no reason to investigate alternate locations.

The optimum free surface loss due to a stabilizer is in the range of 20 to 35% of the uncorrected GM. The free surface loss of the stabilizer in this application, assuming that all of the wing space is utilized, ranges from about 12% to about 40% of the uncorrected GM. (See Table 1) For the full load condition it would be better to have a larger free surface loss. However, if the free surface loss were increased, there would be excessive free surface loss in the nearly burned out load condition. Considering that the stabilizer must be effective and usable over the entire operating range, the allocated wing space results in a free surface loss which is practically optimum (pun intended).

A preliminary study of the effects of tank damping ratio showed that the roll motions are only slightly affected by this parameter over a realistic range, and that the roll motions are least for the lowest values of tank damping ratio. Therefore, each tank configuration analyzed was assigned a damping ratio estimated to be the lowest value consistent with design constraints.

The problem of optimizing the stabilizer dynamic characteristics reduces to selecting the optimum resonant period. To accomplish this, the ship/stabilizer performance calculations were performed for a parametric series of stabilizers, each with a different resonant period. Resonant periods analyzed included 9, 10, 11, 12 and 13 and 14 seconds.

The resonant period of the stabilizer is determined by the geometry of the duct. The parametric variation of resonant period therefore represents a parametric variation in the duct geometry. Once the "optimum" range resonant period was established, duct geometries which would result in periods near the optimum were determined. The stabilizer geometries resulting from this process are illustrated in Figures 1 and 2.

Note in the figures that configurations "A" and "B" violate the allocated envelope for the stabilizer. The duct has been lowered 1.5 feet below the 01 level. This lowering of the duct is recommended in order to provide adequate headroom in way of the duct at the 01 level. Configuration "D" also violates the allocated envelope, encroaching into the corners of the fan rooms to increase the volume of the duct slightly.

These configurations are discussed in more detail in the "Discussion of Results" section of this report.

LINEAR ANALYSIS OF STABILIZED SHIP PERFORMANCE

Introduction

In order to ascertain the expected roll stabilization of several of the stabilization systems, a computer-aided simulation of the behavior of the ship was performed for various random seaways and directions to the seaway for both zero speed and 12.5 knots forward way. In this section the computations based on the linearized model of the problem and the computer output are described. The results of this simulation are expected to be indicative of the ship and tank performance over a wide range of ocean environments in which the excitation is moderate. These results have proved to be representative of more sophisticated calculations which include such nonlinearities as quadratic tank damping, nonlinear roll damping, nonlinear restoring moment, and tank slamming (saturation), provided that the tank slamming occurs less often than every third cycle, and that the other nonlinear effects are properly modeled by equivalent linear terms.

Formulation of Linear Problem

The linearized simulation of the behavior was achieved with a digital computer program which is based on the formulation presented in reference 1. In this model, the ship roll, sway, yaw, and the tank angle are derived from a set of five coupled linear differential equations. The system properties, i.e., the hydrodynamic forces and moments, are computed on the basis of a slender-ship theory, and the forcing functions due to the seaway allow for hydrostatic, velocity and acceleration effects. The equations of motion used in the linear analysis are obtained from Equations (24), (25), (26), and (27) of reference 1 by retaining only the linear terms. The forcing functions are given by Equations (51), (52), (53), (54), (55) and (56) in the same reference.

Summary of Simulated Conditions

Computations based on linear theory were made for both zero speed and 12.5 knots forward way for each of the five loading conditions.

The behavior of the ship/tank system was computed for both regular (single frequency) and irregular (wave spectrum) waves. Irregular waves were modeled by the Pierson-Moscowitz spectrum corresponding to five sea states of significant wave heights of 8, 12, 20, 30 and 40 feet. The irregular seas were assumed to be both long-crested (unidirectional) and short-crested (multidirectional). In the case of the short-crested seas the directionality function used was a cosine-squared distribution.

Evaluation Criteria

The output of the simulation includes the ship motions and tank responses to regular waves (unit responses) and the statistical responses to both short-crested and long-crested seas. The following discussion is intended to provide guidance in the understanding and evaluation of these measures of the stabilizer performance.

The unit response of the ship at resonance is typically the most obvious single measure of performance. Stabilizer tanks are usually designed to minimize the ship roll response at resonance. For most ships underway in quartering seas, a stabilizer which minimizes roll response at resonance is very effective at reducing the rolling motions in the seaway, since under this condition many of the waves in the sea may be encountered at frequencies near roll resonance even though the waves are of higher frequencies.

The statistical roll motions of the ship are the most meaningful measure of performance.

To arrive at the summary of results for long-crested and short-crested seas, the statistical responses of the system are calculated over a range of headings relative to the sea from head sea to following sea, that is 0° to 180° at 15° intervals. The standard deviation (or rms, root mean square) of each response is computed. The largest value obtained over all headings is utilized in the summary of results. The results are presented in rms values because of the convenience in using them to determine the statistics of the motions. The following table provides typical conversions.

	half band-width (amplitude)	whole band-width (out-to-out motion)
Average		
all cycles	1.25 rms	2.50 rms
1/3 highest (significant)	2.00	4.00
1/10 highest	2.55	5.10
Value exceeded once per		
100 cycles	3.04	6.08
1000 cycles	3.72	7.44

The long-crested seaway statistics are obtained by multiplying the appropriate response amplitude operators (unit responses) by the relevant sea spectrum and integrating over the whole frequency domain. Thus, frequencies which cause large motions near resonance are included as well as those which do not cause severe motions. Since the tank reduces roll primarily at resonance, the roll reduction afforded by the stabilizer in a seaway, where many frequencies are present, is less than the roll reduction at resonance.

The short-crested seaway responses are formed by integrating the long-crested seaway responses over a range of track-to-wave angles, including headings which cause large motions and those which do not. As a result, the roll reductions attributed to the tank stabilizer are yet again less than those due to long-crested seas. Although discussion of the ship response in short-crested seas therefore leads to the smallest numerical values for roll reduction, these results are most meaningful since they represent most closely the values that one would measure in a real sea. The long-crested results are more appropriate to swell conditions.

The motions of the water in the stabilizer tank are important in the evaluation of the results. These motions are characterized by the "tank angle", the roll angle of the water in the tank relative to the ship. Saturation of the tank (slamming of the water in the tank against the top of the tank) occurs at a tank angle which depends on the geometry of the tank and the level of water in the tank. Examining the statistical (rms) tank angles in a seaway, one can expect incipient saturation to occur regularly (every seventh or eighth roll) when the rms tank angle is half the tank saturation angle. At this point the tank effectiveness is only slightly degraded by the saturation. One can expect significant saturation when the rms tank angle is 75 percent of the tank saturation angle. At this point and beyond, the effectiveness of the tank is severely degraded by the saturation phenomenon. The linearized theory does not include the effects of tank saturation, so the tank statistics must always be examined to assure that the computed roll reduction can reasonably be expected to be realized.

Results of Analysis

The results of the linear analysis are summarized in Tables 2, 3, and 4. Table 2 shows the maximum value of the roll response amplitude operator in regular waves from abeam. Table 3 displays the standard deviation (rms) of roll angle at the worst headings in short-crested seas. Table 4 presents the standard deviation of the angle of the water in the stabilizer at the worst headings in short-crested seas.

The ship roll response to regular waves from abeam with zero forward way is presented graphically in Figure 3 for the Eastern Arctic "Full Load" and 50% Fuel" load conditions for three cases: no stabilizer, stabilizer with 10 second period, and stabilizer with 11 second period.

SELECTION OF STABILIZER CONFIGURATION

Selection of Stabilizer Resonant Period

To select the "optimum" stabilizer resonant period, we must choose a period which results in low values of rms roll angle over the full range of operating conditions. The response amplitude operators in Table 2 indicate the worst response to a swell from abeam, but are otherwise not particularly significant. The rms roll angles presented in Table 3 are the most meaningful measure of the stabilizer performance. The optimum stabilizer period for each combination of load condition, speed and sea state has been marked with an asterisk (*) in Table 3. The optimum period varies with load condition, speed, and even sea state. Scanning the table, and placing the most weight on results for the "50% Fuel" load conditions with forward way, it is clear that the optimum period is about 10 seconds or slightly higher.

It is important to understand the consequences of selecting a stabilizer configuration with a particular period. The results listed in Table 3 are for the ship with the values of GM estimated in the preliminary design. If the ultimate GM of the ship changes, it may be desired or even necessary to modify the stabilizer to be more nearly optimum for the ship as built. If the ship's GM is lower than the values used in this study, then the stabilizer could be matched to the ship by blocking off part of the crossover duct, increasing the period. On the other hand, if the GM turns out to be higher than expected, then optimizing the stabilizer would require enlarging the duct, a costly modification at that point. When in doubt, it is prudent to select a stabilizer with a low period and large duct.

Stabilizer Duct Geometry

An analysis, by empirical methods, of the effects of the duct geometry on the stabilizer period has resulted in the stabilizer configurations shown in Figures 1 and 2 and described in Table 5. Two factors have been considered in devising these duct geometries. First, it is desired to have a stabilizer resonant period of about 10 seconds. Second, it would be beneficial to arrangements if adequate headroom were available in the spaces both above and below the duct.

Configuration D utilizes only the space allocated to the crossover duct (12.5 feet long, 3.0 feet high). The resulting resonant period is about 10.8 seconds, higher than desired. In the stowage area on the 01 level in way of the duct the headroom is only about 5.0 feet.

Configuration C is only slightly different from Configuration D. Here the duct is enlarged slightly at the forward outboard corners, utilizing some space not allocated to the stabilizer in the arrangement drawings. This modification represents a slight improvement over Configuration D, in that both the resonant period and the damping ratio are decreased, two beneficial effects.

To decrease the resonant period to lower than about 10.7 seconds will require enlarging the duct significantly. A period of about 10.1 seconds can be achieved if the duct height is increased to 3.5 feet. However, at this duct height the remaining headroom on the 01 level in way of the duct becomes intolerably small. To ameliorate the problem with headroom and simultaneously to decrease the stabilizer resonant period, we recommend that the bottom of the duct be lowered by about 1.5 feet, as in Configurations A and B.

In Configuration B the duct height remains at 3.0 feet. With this configuration the problem with headroom is alleviated, but there is no performance advantage over Configuration D.

In Configuration A the duct height is increased to 3.5 feet. The resonant period is about 10.1 seconds, practically optimum. Headroom appears to be adequate in all spaces. Configuration A is the recommended configuration.

Even Configuration A could be improved slightly by enlarging the duct at its forward corners. In this configuration, however, the sloping deck at the bottom of the wing tank would have to be extended forward to the forward end of the wing tank. For the performance of the stabilizer this would be a desirable modification, but the adverse effect on arrangements may outweigh the advantage. We recommend this modification.

Stabilizer Height

The motions of the water in the stabilizer, presented in Table 4, can be used to size the height of the tank necessary to avoid the performance being degraded by saturation. Scanning the results for the 10 second period stabilizer, it is clear that the maximum rms tank angle is about 10 degrees. Incipient saturation will occur if the tank geometry allows for twice this value, or about 20°. Assuming the tank is filled to half its height, the tank height required by this criterion is about 17 feet. The water height would be 8.5 feet. We recommend a tank height of 18 feet or more, and a water height of 9 feet.

Air Crossover Pipe

To avoid sonic flow in the air crossover pipe, a pipe diameter of 1.5 feet is recommended. This diameter provides a cross sectional area sufficient to hold the air velocity to less than 500 feet per second in the most extreme case. The pipe may be equipped with a butterfly valve, if desired. Closing this valve would eliminate the free surface loss of the stabilizer for temporary operations in which high GM is desired. If the butterfly valve is installed, then only one of the wing tanks should be vented.

RECOMMENDATIONS

Ship Research Incorporated recommends selection of Configuration A, Figure 2, for the stabilization of the Dual Draft Icebreaker. The bottom of the duct of this configuration is 1.5 feet below the 01 level, and is 3.5 feet high, leaving headroom of 6.5 feet in the mess hall under the duct and 6.0 feet in the stowage area above the duct (allowing 0.5 feet for structure). The water in the stabilizer weighs 129 tons.

The recommendation of this stabilizer configuration is based on a desire for a resonant period near 10 seconds, which would be about optimum. It also would provide some margin for error on matching the stabilizer to the ship in the event that the GM as built is higher than the preliminary design estimates.

If Configuration A is for some reason unacceptable, Configurations B, C, and D are recommended in that order. Any of these configurations would provide good roll stabilization, but Configuration A is best for most operating conditions.

Configuration C utilizes some space from the corners of the fan rooms for increasing the duct volume. A similar use of this space for Configurations A or B would be desirable. A sloping deck would be required on the bottom of the wing, as illustrated in Figure 2, all the way to the forward end of the wing tank, in order to provide continuity of flow from the duct into the wing tank in the enlarged region.

Regardless of the configuration selected, the internal geometry of the duct should be as free of structural members and other obstructions as is reasonably feasible. Structural members inside the duct increase both the resonant period and damping of the stabilizer with deleterious effects on performance.

REFERENCES

1. Webster, W. C., "Analysis of the Control of Activated Antiroll Tanks", Transactions of the Society of Naval Architects and Marine Engineers, Volume 75, 1967, page 296.

2. "Preliminary Design Report for a Dual Draft Icebreaker", Naval Engineering Division, Electronics Engineering Division, U. S. Coast Guard, November 1, 1979.

3. "296-Foot WAGB Lines & Offsets", U. S. Coast Guard Naval Engineering drawing, provided by R. D. Fuller, Jr.

4. "Dual Draft Icebreaker Arrangements, Main Deck & 01 Level", U. S. Coast Guard Naval Engineering drawing dated 7/1/80, provided by R. D. Fuller, Jr.

	Eastern Arctic		Great Lakes		
	Full Load	50% Fuel	Full Load	50% Fuel	Burned Out
Displacement, LT	7018	6177	6247	5768	5290
Draft, ft.	24.30	23.10	22.80	21.80	20.10
KG,ft.	22.29	24.12	22.67	24.12	25.84
KB,ft.	13.68	13.00	12.90	12.30	11.40
GM,ft.	5.39	3.93	5.33	3.81	2.06
Roll Period, sec.	10.68	13.07	11.23	13.28	18.06
Stabilizer % GM loss*	11.7	19.9	14.2	21.5	43.3

*assuming all of allocated wing tanks utilized

Table 1. SUMMARY OF SHIP LOADING CONDITIONS

Loading Condition	Speed knots	None	Stabilizer Period, Sec. T=9	T=10	T=11	T=12
Eastern Arctic Full Load	0	7.40	1.17	1.25	1.58	1.95
	12.5	4.18	1.04*	1.14	1.41	1.68
Eastern Arctic 50% Fuel	0	5.15	0.71	0.63*	0.63	0.76
	12.5	2.61	0.61	0.56*	0.59	0.71
Great Lakes Full Load	0	6.88	0.98	0.97*	2.21	1.51
	12.5	3.74	0.88*	0.90	1.10	1.33
Great Lakes 50% Fuel	0	5.07	0.65	0.59	0.58*	0.70
	12.5	2.50	0.56	0.52*	0.55	0.66
Great Lakes Burned Out	0	2.84	0.23	0.21	0.21*	0.22
	12.5	1.14	0.25	0.24	0.23*	0.24

Note: Values are amplitude of roll angle per amplitude (one-half height) of wave, degrees/foot

Table 2. SUMMARY OF MAXIMUM VALUES OF ROLL RESPONSE AMPLITUDE OPERATOR IN BEAM SEA REGULAR WAVES

Loading Condition	H_{sig} ft.	Speed = 0 Unst.	T=9	T=10	T=11	T=12	Speed = 12.5 knots Unst.	T=9	T=10	T=11	T=12
Eastern Artic Full Load	8	1.9	0.9*	1.0	1.1	1.2	4.0	2.4	2.3*	2.4	2.6
	12	5.5	1.9*	2.2	2.5	2.8	6.2	3.5	3.5*	3.7	3.9
	20	10.2	3.7*	4.0	4.4	4.9	8.7	5.0	4.9*	5.1	5.4
	30	12.5	5.1*	5.2	5.7	6.2	10.2	6.0	5.9*	6.1	6.4
	40	13.5	5.8*	6.0	6.4	6.9	10.9	6.6	6.5*	6.7	7.0
Eastern Artic 50% Fuel	8	0.4	0.4*	0.4	0.4	0.4	5.7	3.1	2.9	2.8*	2.9
	12	1.8	0.8*	0.9	1.0	1.1	8.4	4.5	4.2	4.1*	4.2
	20	5.9	1.8*	2.0	2.2	2.5	11.5	6.3	5.8	5.6*	5.6
	30	9.1	3.1*	3.2	3.4	3.8	13.4	7.5	6.9	6.6*	6.7
	40	10.8	4.2	4.1*	4.3	4.6	14.3	8.1	7.5	7.2*	7.3
Great Lakes Full Load	8	1.3	0.7*	0.8	0.9	1.0	4.9	2.6	2.5*	2.6	2.7
	12	4.6	1.5*	1.7	2.0	2.2	7.1	3.8	3.7*	3.8	4.0
	20	9.9	3.1*	3.4	3.8	4.2	9.6	5.3	5.1*	5.3	5.5
	30	12.9	4.6*	4.7	5.1	5.5	11.0	6.3	6.2*	6.3	6.5
	40	14.2	5.4*	5.5	5.8	6.3	11.8	7.0	6.8*	6.9	7.1
Great Lakes 50% Fuel	8	0.4	0.4*	0.4	0.4	0.4	6.1	3.1	2.9	2.9*	3.0
	12	1.5	0.8*	0.9	1.0	1.0	9.0	4.6	4.3	4.2*	4.3
	20	5.3	1.7*	1.8	2.1	2.3	12.1	6.4	5.9	5.7*	5.8
	30	8.5	2.9*	3.0	3.3	3.6	14.1	7.6	7.0	6.7*	6.8
	40	10.3	4.0	3.9*	4.1	4.4	15.0	8.3	7.7	7.4*	7.5
Great Lakes Burned Out	8	0.2	0.3	0.3	0.3	0.2*	5.5	2.2*	2.2	2.3	2.4
	12	0.3	0.5	0.5	0.5	0.4*	7.9	2.9*	3.0	3.1	3.3
	20	1.5	0.8*	0.8	0.8	0.9	12.2	3.8*	3.9	4.1	4.4
	30	6.1	1.0*	1.1	1.2	1.3	16.0	4.7*	4.8	5.0	5.3
	40	10.5	1.3*	1.4	1.6	1.8	18.1	5.5*	5.5	5.7	6.0

Table 3. SUMMARY OF COMPUTED RMS ROLL ANGLES AT WORST HEADINGS IN SHORT-CRESTED SEAS SHIP WITH AND WITHOUT STABILIZER. PARAMETRIC VARIATION OF STABILIZER NATURAL PERIOD.

Loading Condition	H_{sig} ft.	Speed = 0 T=9	Speed = 0 T=10	Speed = 0 T=11	Speed = 0 T=12	Speed = 12.5 knots T=9	Speed = 12.5 knots T=10	Speed = 12.5 knots T=11	Speed = 12.5 knots T=12
Eastern Arctic Full Load	8	2.4	2.1	1.8	1.5	4.0	3.6	3.2	2.8
	12	4.4	4.0	3.6	3.2	5.8	5.2	4.6	4.1
	20	7.1	6.5	5.9	5.3	7.8	7.0	6.2	5.5
	30	8.8	8.0	7.2	6.5	9.0	8.1	6.2	6.4
	40	9.6	8.6	7.8	7.0	9.6	8.6	7.7	6.8
Eastern Arctic 50% Fuel	8	1.6	1.3	1.1	0.9	4.6	4.2	3.9	3.6
	12	2.7	2.4	2.1	1.9	6.6	6.0	5.5	5.1
	20	4.6	4.3	4.0	3.6	3.9	8.1	7.3	6.7
	30	6.3	5.8	5.4	5.0	10.3	9.3	8.5	7.8
	40	7.3	6.8	6.3	5.8	11.0	10.0	9.2	8.4
Great Lakes Full Load	8	2.1	1.8	1.5	1.3	4.2	3.8	3.4	3.1
	12	3.8	3.5	3.1	2.8	6.1	5.5	4.9	4.4
	20	6.4	5.9	5.4	4.9	8.2	7.4	6.6	5.9
	30	8.1	7.4	6.7	6.1	9.4	8.5	7.6	6.8
	40	8.9	8.1	7.4	6.7	10.0	9.0	8.1	7.2
Great Lakes 50% Fuel	8	1.6	1.3	1.1	0.9	4.7	4.3	4.0	3.7
	12	2.7	2.4	2.1	1.8	6.7	6.2	5.7	5.2
	20	4.5	4.2	3.8	3.5	9.1	8.3	7.6	6.9
	30	6.1	5.7	5.3	4.9	10.5	9.5	8.7	8.0
	40	7.2	6.6	6.1	5.7	11.2	10.3	9.4	8.6
Great Lakes Burned Out	8	1.3	1.0	0.8	0.7	3.3	3.3	3.3	3.2
	12	2.9	1.7	1.4	1.2	4.5	4.5	4.5	4.4
	20	3.0	2.7	2.4	2.1	6.1	6.1	6.0	5.9
	30	3.7	3.4	3.2	2.9	7.3	7.3	7.2	7.1
	40	4.2	4.0	3.8	3.5	8.3	8.2	8.0	7.6

Table 4. SUMMARY OF MAXIMUM TANK ANGLES IN SHORT-CRESTED SEAS, PARAMETRIC VARIATION OF STABILIZER PERIOD

Configuration	Period sec.	Water Height LT	Headroom in Way of Duct, ft* 01 level	main deck
A. Duct bottom 1.5' below 01 level Duct height 3.5' (2.0' above 01 level)	10.1	129	6.0	6.5
B. Duct bottom 1.5' below 01 level Duct height 3.0' (1.5' above 01 level)	10.8	123	6.5	6.5
C. Duct bottom at 01 level Duct height 3.0' Duct includes corners of fan rooms	10.7	118+	5.0	8.0
D. Duct bottom at 01 level Duct height 3.0'	10.8	118-	5.0	8.0

* 0.5' allowed for structure

Table 5. SUMMARY OF CANDIDATE STABILIZER CONFIGURATIONS

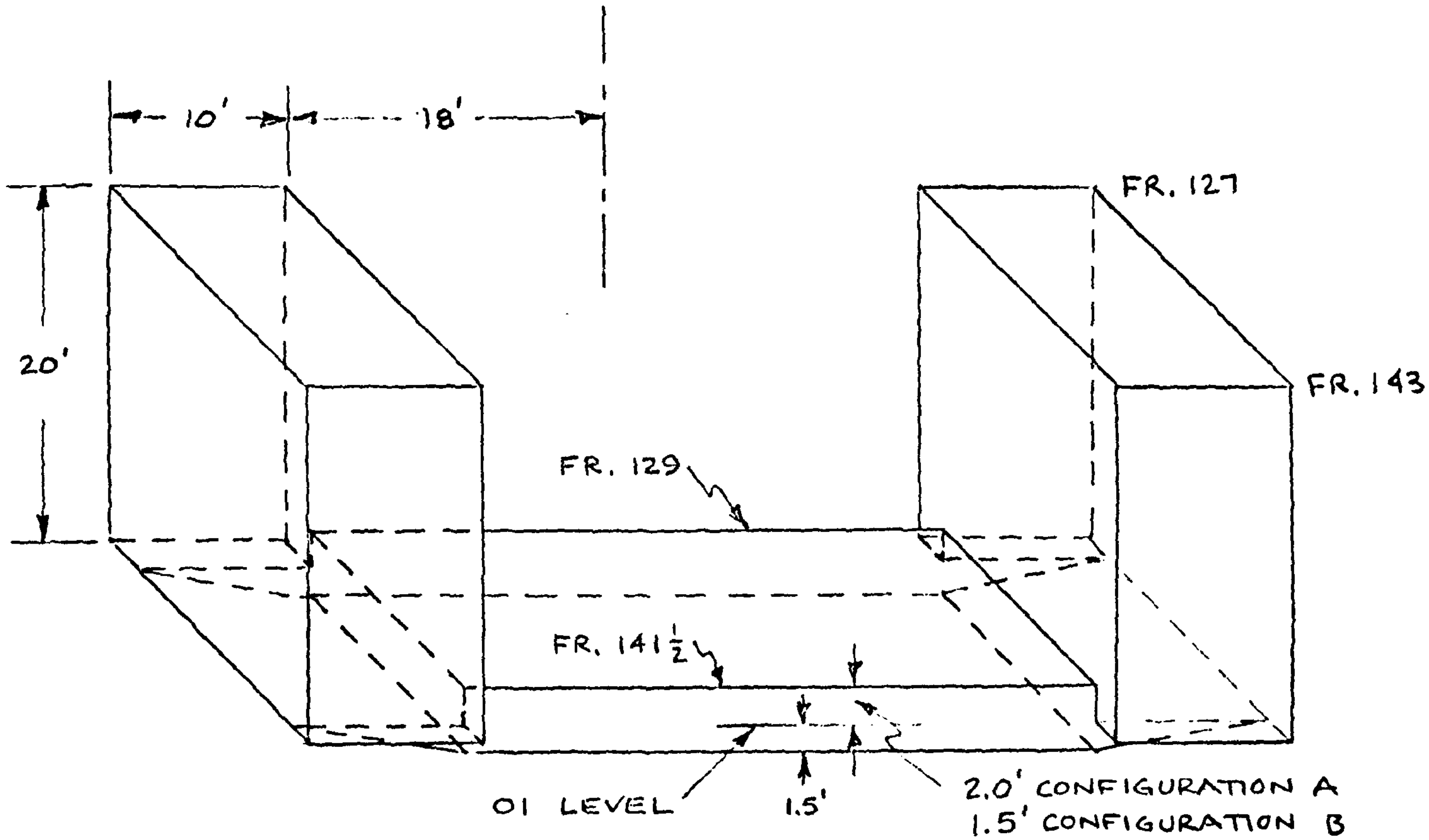

Figure 1. CANDIDATE STABILIZER CONFIGURATIONS A and B

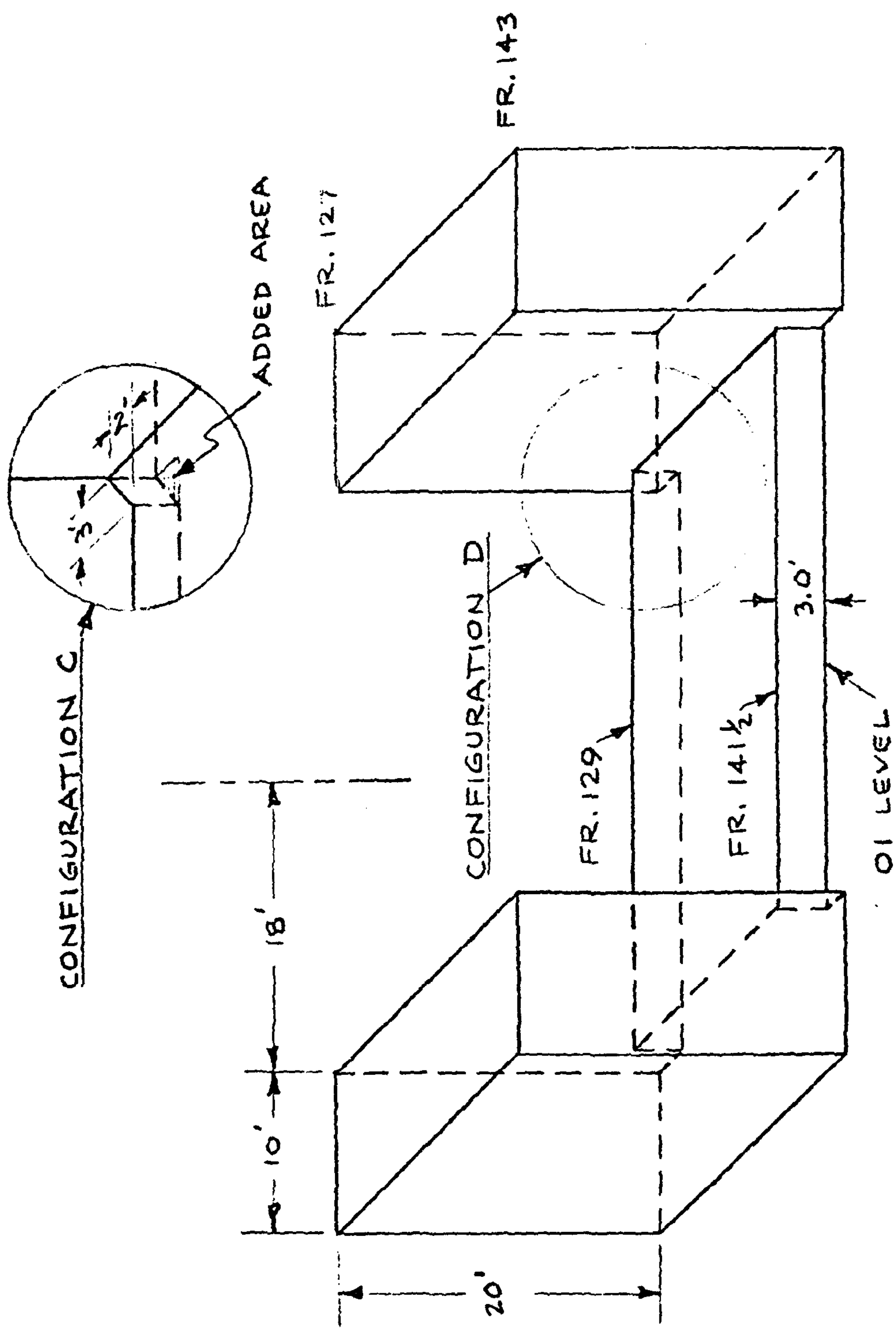

Figure 2. CANDIDATE STABILIZER CONFIGURATIONS C and D

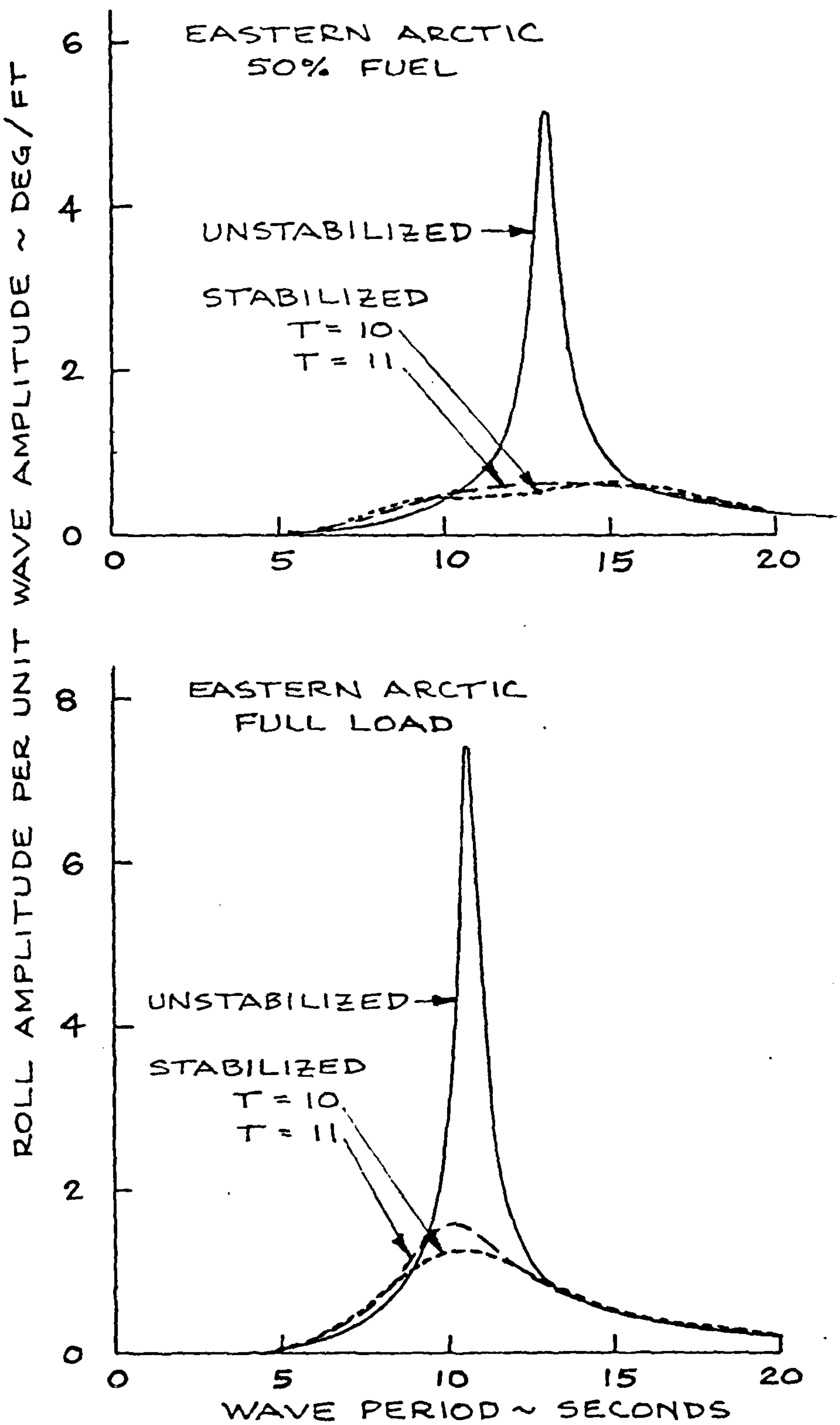

Figure 3. ROLL RESPONSE AMPLITUDE OPERATORS FOR EASTERN ARCTIC LOAD CONDITIONS, ZERO SPEED, WAVES FROM ABEAM

APPENDIX B

"Comparative Model Tests of U-Tube
and Free Surface Roll Stabilizer Designs
for the United States Coast Guard Dual Draft Icebreaker"

Davidson Laboratory Report SIT-DL-81-9-2166
November 1980

STEVENS INSTITUTE OF TECHNOLOGY
DAVIDSON LABORATORY
CASTLE POINT STATION
HOBOKEN, NEW JERSEY

SIT-DL-80-9-2166
November 1980

COMPARATIVE MODEL TESTS OF U-TUBE AND FREE-SURFACE ROLL STABILIZER DESIGNS FOR THE USCG DUAL DRAFT ICEBREAKER

by

John F. Dalzell

Prepared for

United States Coast Guard (G-ENE-5D)

under

Office of Naval Research

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(Davidson Laboratory Project 4853/093)

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Daniel Savitsky
Deptuy Director

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INTRODUCTION

The purpose of the work reported herein was to make direct experimental comparisons between two alternate roll stabilizer tank designs for the USCG Dual Draft Icebreaker.* Both stabilizers were allocated the same 01-level space (between frames 129 and 143), one design was to be a U-tube, and the other a free surface type stabilizer.

Neither of the stabilizer designs was to be prepared by Davidson Laboratory. The designer of the free-surface tank was the David W. Taylor Naval Ship Research and Development Center, and the designer of the U-tube tank was Ship Research Incorporated of Kensington, California.

Once the respective designers had made their analysis, bench tests, and recommendations, the role of the Davidson Laboratory was to make simple model tests to verify and compare the two designs.

The specific scope of work for this effort included:

1. Fabrication of two 1/48 scale stabilizer tank models such that they could be alternately installed in an existing 1/48 scale model of the ship.
2. Outfitting and ballasting the model to represent the design displacement, draft, KG, and roll period.
3. Test the model in the hove-to condition in beam regular waves of varying length and a single moderate height, with additional runs made in the vicinity of resonance with larger and smaller wave heights. These tests were to be repeated with each stabilizer in operation.
4. Prepare the present test report summarizing the results.

SHIP AND MODEL

A 1/48 scale ship model according to the specifications of Reference 1 had previously been cut at the U.S. Naval Acadamy Towing Tank Laboratory in support of other studies for the Dual Draft Icebreaker. This model was of

*1 "Preliminary Design Report for a Dual Draft Icebreaker", United States Coast Guard, Naval Engineering Division and Electronics Engineering Division, 1 November 1979.

suitable size for the present work and was released temporarily to Davidson Laboratory. The model is cut to level sheer at approximately the 47.5 foot waterline. The 01 level where the tanks are located was taken as 50.5 feet above baseline, so that the model tanks were located completely above model sheer. The model was outfitted with bossings and rudder, but no bilge keels.

The nominal design condition for the roll stabilizers was furnished by the Naval Engineering Division, USCG as follows:

Nominal Condition:	Eastern Arctic, 75% fuel
Displacement:	6,646 long tons
Draft:	23.66 feet
Transverse GM:	4.02 feet

It is to be noted in the above that the transverse metacentric height is inclusive of design margins and normal free surface corrections but excludes the free surface correction for the operating stabilizer tanks. All the tests were conducted at this nominal ship condition.

The model was outfitted with a roll/pitch gyro; brackets fore and aft to provide attachment points at the waterline for the restraint used in the experiments; an inclinometer for use in initial ballasting; an inclining weight; brackets to hold the model tanks; some vertically adjustable ballast; mylar decks; and fixed ballast to make displacement. The longitudinal distribution of ballast and outfit was nearly uniform in the mid 80% of length. No check on longitudinal gyradius was made since all tests were to be in beam seas. Initial ballasting prior to the experiments was done with a dummy gyro so as to come close to the desired GM, roll period and trim. For the case that no stabilizer was operating the heavier of the two model stabilizers (the U-tube) was installed with steel tare weights cut so as to simulate the weight of water which was later to be added to make the stabilizer operate. With the model in this condition, inclining experiments were done at the outset of the experiments with all instrumentation connected, so as to trim the transverse GM to that required by the above specification. The roll period was checked by stopwatch with the model in the "no stabilizer" condition and was found to be:

12.8 seconds (full scale)

By the end of the program four stabilizer conditions were run:

1. No Stabilizer
2. Basic U-Tube Stabilizer
3. Free Surface Stabilizer
4. Modified U-Tube Stabilizer

As noted, the transverse stability was checked by inclining for condition 1. The transition to condition 2 was made by removing the water tare weights and adding water. When the free surface stabilizer model was installed, weight was added to make up the lost displacement, and the model was inclined so as to adjust the GM to the specified value less computed free surface correction due to the tank. The transition to case 4 from case 3 was made similarly.

The net effect of the procedure is that in the "no stabilizer" case the fluid in the stabilizer tanks is treated as if it were "frozen", not dumped out.

THE FREE SURFACE ROLL STABILIZER

Figure 1 indicates the geometry of the free surface roll stabilizer which was modeled. The final specification for this tank was received by telephone from the USCG Naval Engineering Division, 3 November 1980. As may be noted in the figure, the tank plan is of the "H" style, 8.5 feet deep, 16 feet fore and aft in way of the wings, and has a 12.5 foot wide crossover (frame spacing is one foot). No internal structure or "nozzles" were specified and none were built into the model tank. The design water depth was 4.0 feet, and this was used throughout the experiments.

The tank model was made of 1/4 inch clear plastic with thicker blocks of the same material inserted to form the crossover constriction. Two details not part of the full scale design are indicated in Figure 1. For experimental convenience the model tank was left uncovered in the area 11 feet (full scale) port and starboard of centerline. Because some aspects of the dynamics of the air in the tank are often badly out of scale, six one foot diameter (full scale) vents were installed port and starboard in the tank covers to prevent air pockets from forming when the tank is near saturation.

It is not usual in commercial free surface stabilizer practice to

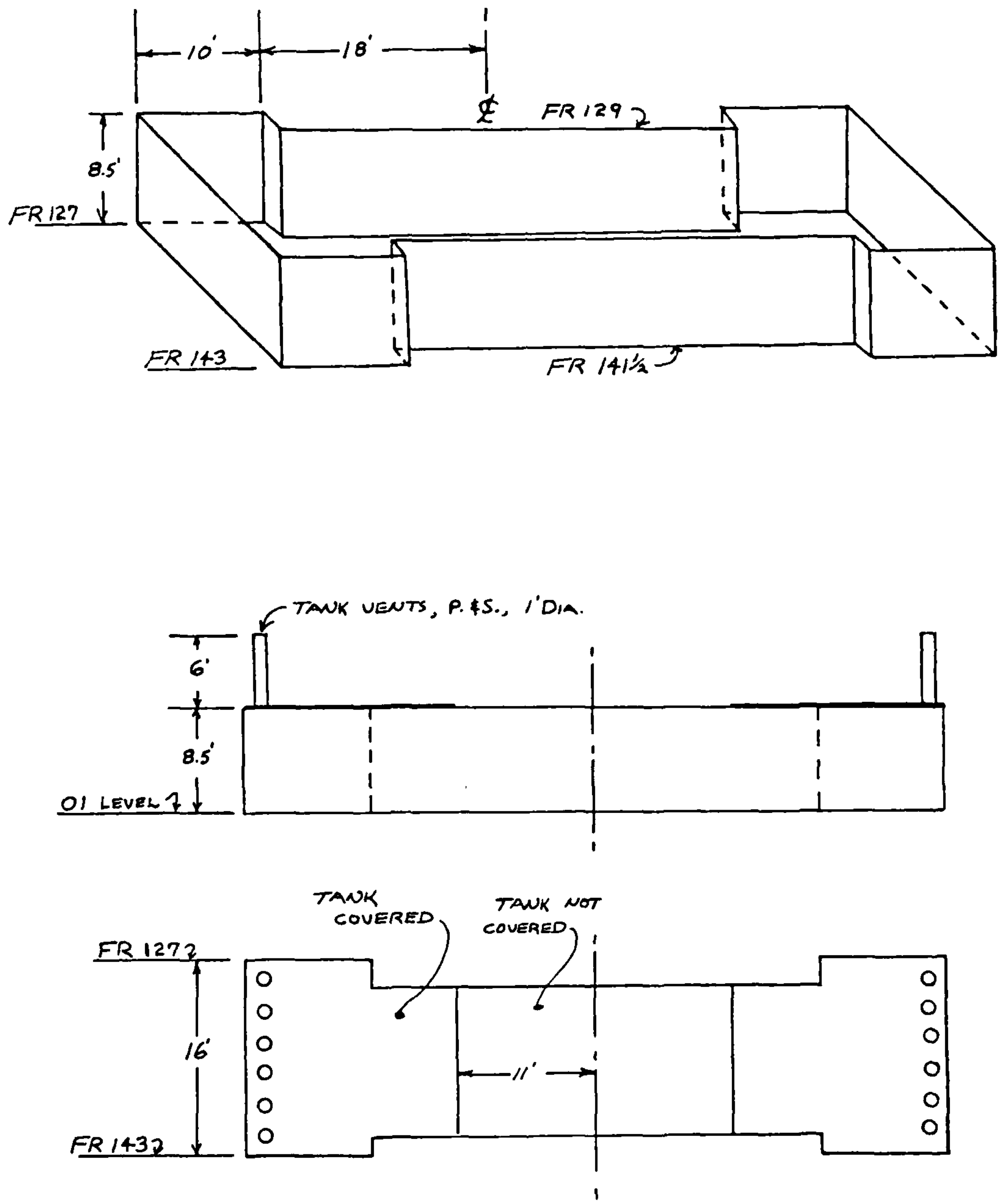

FIGURE 1 THE MODEL FREE SURFACE ROLL STABILIZER

correlate the ship model scale tank dynamics with the designer's larger scale bench model results, and this was not attempted.

THE U-TUBE ROLL STABILIZER

Of the four candidate U-tube stabilizer configurations developed by Ship Research Incorporated in Reference 2* the simplest, "Configuration D", was selected for development of structural details, bench testing, and eventual incorporation into the present tests. Figure 2 indicates the overall geometry of the model stabilizer--less internal structure. This stabilizer occupies the same 01 level plan area as the free surface tank, Figure 1, the dimensions of the free surface in the wings being 10 feet by 16 feet, and the crossover width being 12.5 feet. The total depth of the wing tanks corresponds to two tween deck heights (22 feet) while the depth of the crossover is 3.0 feet. The design depth of water in the tank is 9.0 feet, and this depth was used throughout the experiments. The model tank was made of clear plastic and a removable crossover duct cover was incorporated.

In so far as the present 1/48 scale model is concerned, the modeling philosophy was slightly different than that for the free surface tank. The problem is that the damping of the U-tube, and to a minor extent the period, are apparently controlled by the structure incorporated in the crossover duct. Both of these may be scale dependent in the model size under consideration. The first consequence to the 1/48 scale model is that the air crossover is omitted and large holes are provided in the wing tank covers so as to remove as much as possible the effects of air on the model dynamics. These holes are indicated in Figure 2; the area of each was approximately 70 square feet full scale. Since the roll stabilizing capacity of the tank is related to the amount of free surface in the wing tanks and the influence of wing tank internal structure is considered minimal in this respect, no internal structure was incorporated in the model wing tanks. What remained in order to make the 1/48 scale model dynamically similar to the designer's bench model was to add drag producing obstacles in the crossover duct such as to approximate the tank period and damping found in the larger scale bench tests.

This last was accomplished by trial and error using at 1/48 scale the same transient test technique used by the designers. The test

*2 "Preliminary Design of a Passive U-tube Stabilizer for the United States Coast Guard Dual Draft Icebreaker", Report CG80-1, Ship Research Incorporated, September 1980

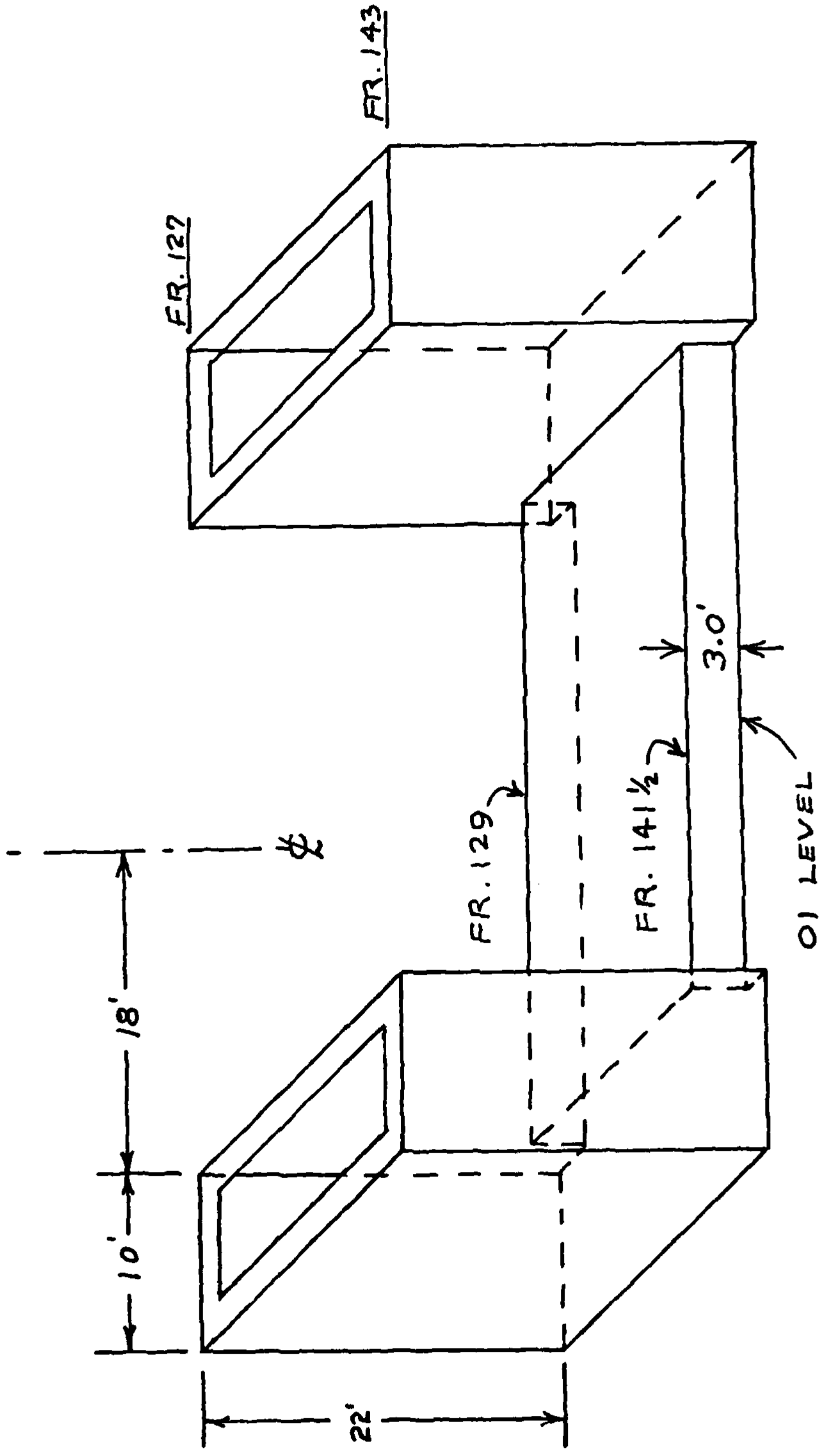

FIGURE 2 OVERALL GEOMETRY OF THE MODEL U-TUBE STABILIZER, Crossover No. 1

technique involves installing a water elevation probe at the center of one wing tank and carrying out the following procedure:

1. Tilt the model to a pre-determined static angle.
2. Prevent further water transfer by capping the air vent on one wing tank.
3. Return the model to level (at this stage the water levels are different port and starboard).
4. Remove the cap as quickly as possible and record the subsequent decay of fluid oscillation.

The results of these transient experiments were compared directly with corresponding bench test data furnished by the designers, and modifications to the crossover duct were made as appeared necessary until reasonable correspondence was found.

At the end of the procedure what is called the "Basic" U-tube model was achieved. The period of oscillation of the 1/48 scale model (as found from the fifth through eleventh oscillations after fluid release) was found to be 11.4 seconds which compares with the designer's result of 11.3 seconds. Figure 3 shows a comparison of the decay of fluid oscillation amplitudes in the 1/48 scale and the bench models. "Tank angle" is defined (in radians) as the ratio of the fluid elevation at the center of the wing to the distance of this point from centerline. For clarity, the points from the bench tests are shown to the left of the appropriate cycle or half cycle line, those from the 1/48 scale experiments are plotted to the right. The results of multiple trials are shown in each case. The agreement is excellent and it was concluded that the "Basic" 1/48 scale U-tube configuration was in good dynamic correspondence with the designer's bench tests.

Figure 4 indicates the detail of four 1/48 scale crossover configurations of pertinence to the present experiments. That at the bottom is the "Basic" U-tube crossover, which provides the results in Figure 3. As noted, 15 (6" x 6") plastic strips which span the duct, and a slightly shorter drag plate in conjunction with a 3 inch decrease in duct height in the middle 30 feet of crossover were necessary.

For reasons which will be noted later, it was decided during the ship model experiments to make a modification to the "Basic" U-tube configuration in the direction of removing "structure" from the crossover. The result is

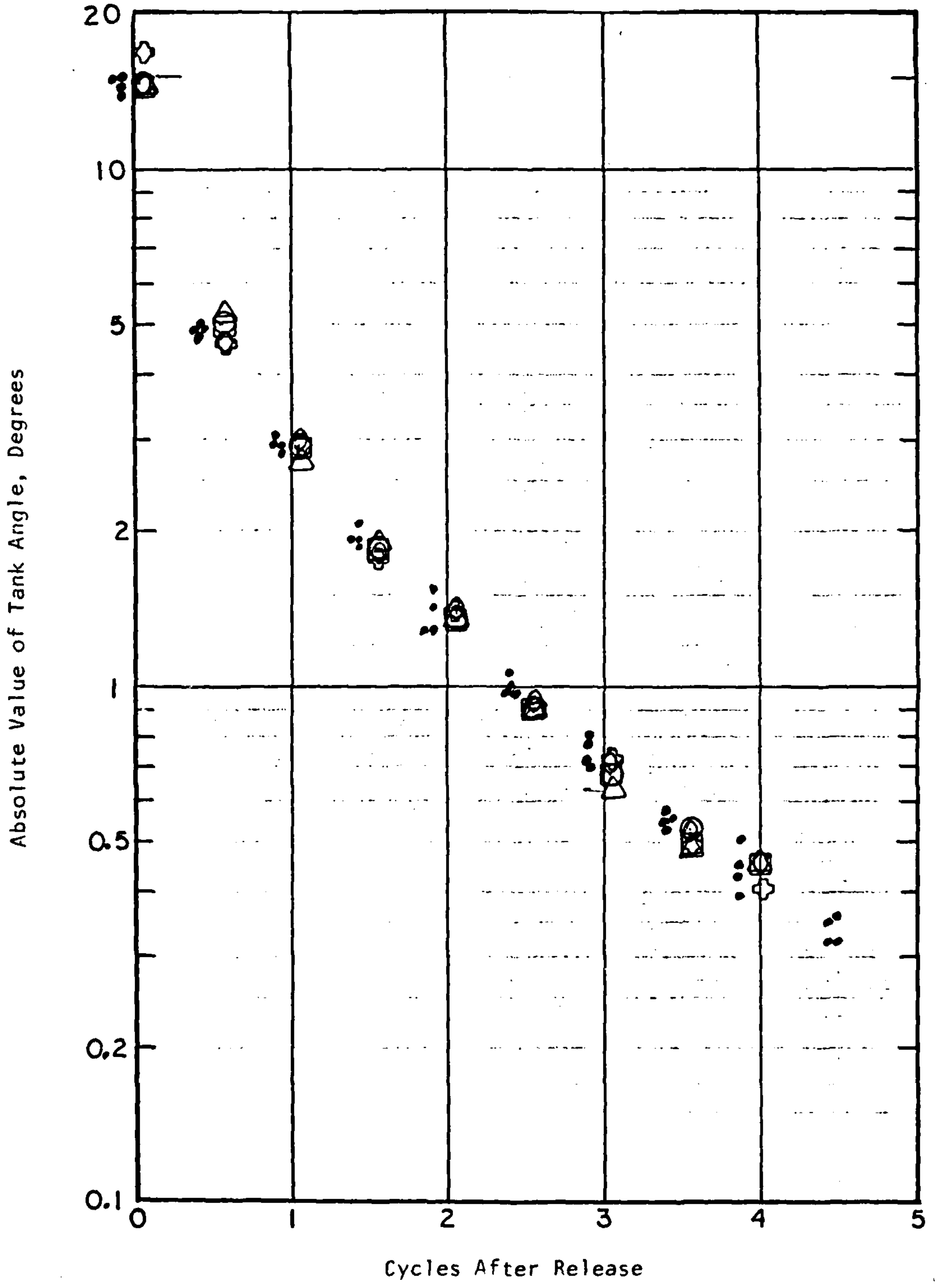

FIGURE 3 COMPARISON OF RESULTS OF TRANSIENT EXPERIMENTS ON 1/48 SCALE "BASIC" U-TUBE (open symbols) WITH THOSE FROM 1/16 SCALE U-TUBE MODEL (dots)

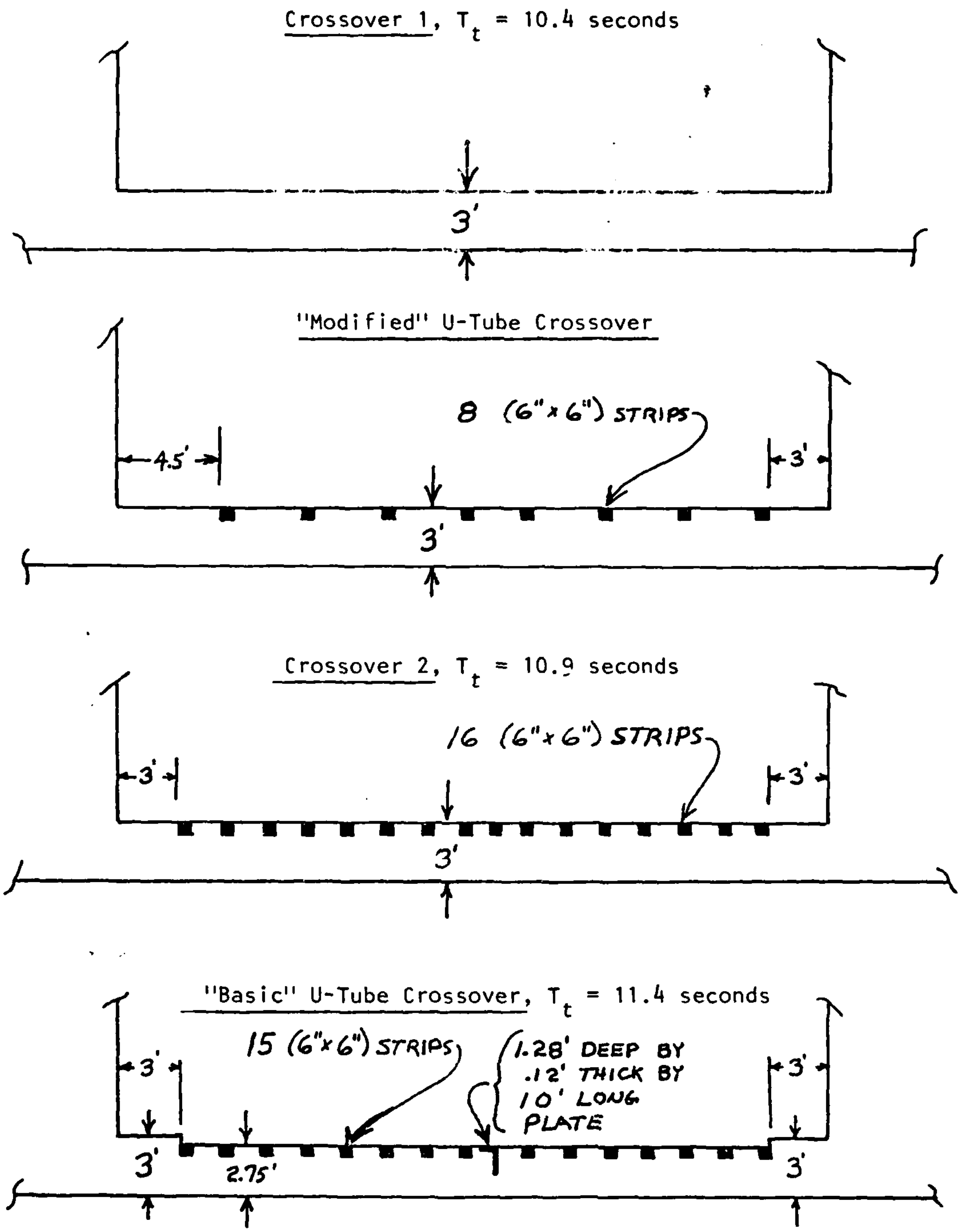

FIGURE 4 1/48 SCALE MODEL U-TUBE STABILIZER
Crossover Configurations

what is called herein the "Modified" U-tube stabilizer. The second crossover configuration from the top of Figure 4 is the net result of this operation. No 1/48 scale bench tests were carried out with this configuration, but in the course of arriving at the "Basic" configuration, data was obtained for two configurations bracketing the "Modified" configuration. These are denoted "Crossover 1" and Crossover 2" in Figure 4, wherein the corresponding tank periods, T_t, are given, Figure 5 indicates the results of the transient experiments with crossover configurations 1 and 2.

EXPERIMENTAL SETUP

The ship model experiments were carried out in Davidson Laboratory Tank No. 3 (300' x 12' x 5.5'). The model was moored at 90^{o} to the tank centerline at about mid position in the tank throughout the experiments. The mooring took the form of a chain of ordinary rubber bands (6) connecting the stem and stern of the model with the sides of the tank. The vertical position of the attachment point was the model waterline and the elastic tethers were horizontal.

Power to and signals from the roll/pitch gyro installed in the model were led ashore through a slack cable supported on the tank towing rail which was directly over model midship. Both roll and pitch angle were recorded on an oscillograph. No appreciable pitching occured, and only the roll motion was pertinent to the results.

A wave probe was installed 10 feet up-wave from the model and the resulting signal was also recorded. It is the general policy at Davidson Laboratory to regard the output of a wave probe close to a large moored model as containing distortions due to waves radiated from the heaving model. For this reason the known calibration of the mechanically driven wave machine, used in conjunction with the mechanically set eccentricity, is considered the best measure of incident wave height. This policy was followed in the present experiments. Accordingly, the main purpose of the wave probe was to aid in the determination of when steady state wave conditions had been attained.

All (except one) of the data runs were recorded on video tape. The equipment used is essentially color home video. The resulting tapes are 1/2" "VHS" system cassettes used in the Standard Play (2 hour) Mode. A

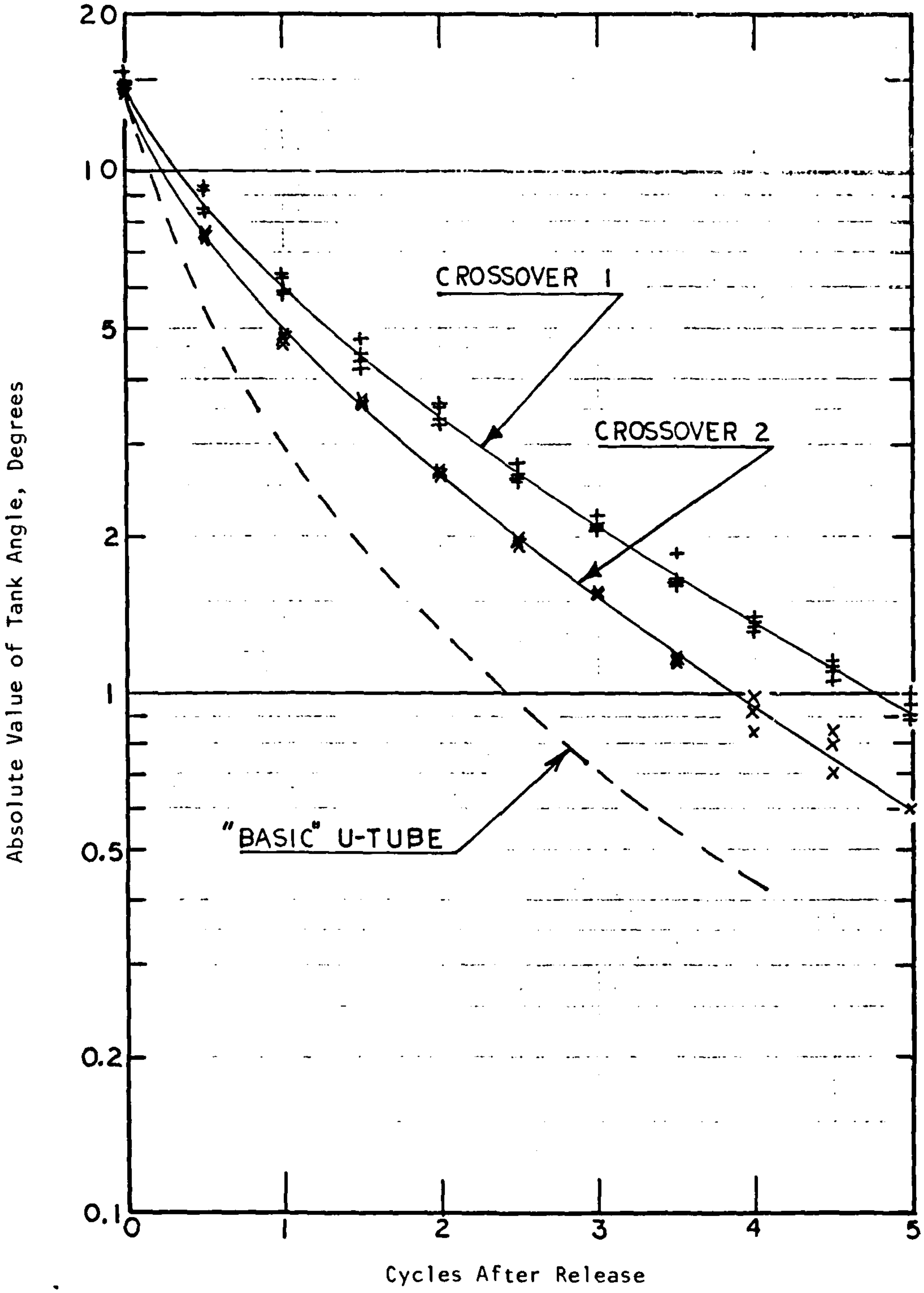

FIGURE 5 RESULTS OF TRANSIENT EXPERIMENTS WITH CROSSOVER CONFIGURATIONS 1 and 2

video typewriter was used both to insert general tape identification and titles, and to superimpose run and parameter identification on all actual data sequences. Accordingly no audio commentary is recorded.

The video camera was adjusted so as to provide a view of the model from a point forward of the bow, slightly to starboard, and at a height which gave a reasonable view of the model stabilizers.

EXPERIMENTAL TECHNIQUES

For each stabilizer condition there were three types of experiments carried out:

1. Roll decrements
2. Regular waves
3. Irregular waves

The roll decrement experiments consisted of heeling the model to about 10° (starboard down) by means of a string tied between the tank rail and a convenient point on the port side of the model directly underneath. When this static adjustment was completed both the oscillograph and video were started, the string was cut, and the declining roll of the model was recorded.

The regular wave experiments comprised the bulk of the present work. The oscillograph was started as the leading waves of each wave train reached the model. When the record indicated that steady state oscillation conditions had been achieved the video tape was started and both video and oscillograph records of about 10 additional wave encounters were obtained. Roll and wave probe double amplitudes were measured from the last part of the records immediately after each run.

The system in use for the generation of irregular waves involves a repeating 100 step wave programmer sequence. Good run-to-run reproducibility of the irregular wave sequence is achieved by recording between specific steps in the program sequence. In the present case half the sequence was required to fill the tank with waves, after which the model response was recorded for one complete 100 step sequence.

CHRONOLOGY

The model experiments were carried out during the three day period 10-12 November 1980. Representatives of Ship Research Incorporated were present 12 November 1980.

Because the video tape record is considered an important part of the reporting of the present work, and has been transmitted to the USCG Naval Engineering Division, a guide to the sequence of events in the video tape is in order. Tables 1 through 4 have been prepared for this purpose as well as to provide a tabulation of the regular wave results.

Each of the four tables pertains to one of the four stabilizer conditions tested (no stabilizer, basic U-tube, free surface, and modified U-tube). Data in the tables is entered in the order obtained. The first three columns in the tables involve the nominal test parameters which appear in the titles on the video tape (run number, wave height, and wave period as applicable). The fourth column gives the approximate video tape footage where the run starts. The fifth through eighth columns pertain only to the regular wave experiments. Video titles must be setup prior to the run with the nominal wave parameters sought. Unfortunately the wave period measured during the run often does not agree exactly with that sought, and accordingly, the scaled actual wave period is recorded in column five. Column 6 of the tables contains the measured steady state roll double amplitude. Column 7 is the ratio of roll double amplitude to wave height, and is thus labeled R.A.O. for response amplitude operator. Column 8 is the ratio of roll double amplitude to twice the computed maximum wave slope. (In the computation of wave slope the influence of water depth on wave length has been taken into account.)

Because of the comparative nature of the tests, the details of the program for the stabilized cases are determined by what happens with the un-stabilized case. Normal practice in this type of test in regular waves is to choose the basic wave height to be used such that the maximum wave slope for the resonant wave is between 2 and 2 1/2 degrees (corresponding to a slope of 4 or 5 degrees). A full scale wave height of 10 ft was chosen for the regular wave tests according to this criterion. Given a roll period of 12.8 seconds, a wave period range between 17 and 9 seconds was desirable.

TABLE 1

CHRONOLOGY AND REGULAR WAVE RESULTS

STABILIZER IN-OPERATIVE

RUN	Wave Height (feet)	Nominal Period (sec)	Video Tape Footage	Actual Period (sec)	Roll Double Amplitude (deg)	R.A.O. (Deg/Ft)	Roll/Wave Slope	Remarks
1	-	-	18	-	-	-	-	Roll Decrement Experiment
2	10.0	17.0	-	-	-	-	-	Video Lost, Bad Waves, No Data
3	10.0	16.0	30	-	-	-	-	Bad Waves, No Data
4	10.0	15.0	36	-	-	-	-	Bad Waves, No Data
5	10.0	15.0	41	14.96	12.75	1.28	3.73	
6	10.0	14.0	51	13.99	19.75	1.98	5.18	
7	10.0	13.5	57	13.44	33.00	3.30	8.09	
8	10.0	13.2	63	12.95	39.50	3.95	9.09	
9	10.0	12.8	69	12.81	42.00	4.20	9.49	
10	10.0	12.4	74	12.33	52.20	5.22	11.00	
11	10.0	12.0	80	11.91	39.60	3.96	7.84	
12	10.0	11.0	84	10.94	-	-	-	Oscillograph Record Lost
13	10.0	11.0	90	10.87	9.75	.98	1.63	
14	10.0	10.0	94	9.98	5.85	.58	.83	
15	10.0	9.0	98	9.00	4.25	.42	.49	
16	5.0	12.4	102	12.26	20.80	4.16	8.68	
17	2.5	12.4	105	12.33	7.70	3.08	6.49	
18	15.0	-	110	-	-	-		Irregular Waves (Data Part Lost)
19	15.0	-	134	-	-	-		Irregular Waves (Repeat of #18)
20	10.0	12.4	156	12.26	52.00	5.20	10.86	
21	2.5	12.8	161	12.68	18.90	7.56	16.75	
22	2.5	13.2	164	13.02	19.00	7.60	17.65	
23	2.5	13.5	168	13.44	6.75	2.70	6.62	

TABLE 2

CHRONOLOGY AND REGULAR WAVE RESULTS

BASIC U-TUBE STABILIZER IN OPERATION

RUN	Wave Height (feet)	Nominal Period (sec)	Video Tape Footage	Actual Period (sec)	Roll Double Amplitude (deg)	R.A.O. (Deg/Ft)	Roll/Wave Slope	Remarks
24	-	-	171	-	-	-	-	Roll Decrement Experiement
25	10.0	15.0	179	14.96	6.15	.62	1.80	
26	10.0	14.0	181	13.92	4.90	.49	1.28	
27	10.0	13.5	183	13.58	5.25	.52	1.31	
28	10.0	13.2	185	13.30	5.35	.54	1.29	
29	10.0	12.8	187	12.89	6.00	.60	1.37	
30	10.0	12.8	189	12.75	6.10	.61	1.36	
31	10.0	12.4	191	12.33	6.60	.66	1.39	
32	5.0	12.4	193	12.33	2.32	.46	.98	
33	2.5	12.4	196	12.40	1.30	.52	1.11	
34	10.0	12.0	197	11.98	7.75	.78	1.55	
35	10.0	11.0	201	10.94	8.80	.88	1.49	
36	10.0	10.0	203	9.84	8.10	.81	1.11	
37	10.0	9.0	205	8.94	6.50	.65	.74	
38	15.0	-	208	-	-	-	-	Irregular Waves

TABLE 3

CHRONOLOGY AND REGULAR WAVE RESULTS
FREE SURFACE TANK IN OPERATION

RUN	Wave Height (feet)	Nominal Period (sec)	Video Tape Footage	Actual Period (sec)	Roll Double Amplitude (deg)	R.A.O. (Deg/Ft)	Roll/ Wave Slope	Remarks
39	-	-	227	-	-	-	-	Roll Decrement Experiment
40	10.0	15.0	235	14.96	3.85	.38	1.12	
41	10.0	14.0	238	13.99	2.15	.22	.56	
42	10.0	13.5	240	13.57	2.65	.26	.66	
43	10.0	13.2	242	13.16	2.00	.20	.47	
44	10.0	12.8	244	12.82	2.25	.22	.51	
45	10.0	12.4	246	12.40	2.65	.26	.56	
46	5.0	12.4	248	12.40	.72	.14	.31	
47	2.5	12.4	251	12.26	.34	.14	.28	
48	10.0	12.0	253	11.98	3.12	.31	.62	
49	10.0	11.0	254	10.95	3.76	.38	.64	Tank Saturation
50	10.0	10.0	257	9.84	5.08	.51	.70	Tank Saturation
51	10.0	9.0	258	8.93	5.70	.57	.65	Tank Saturation
52	10.0	11.5	260	11.43	4.04	.40	.74	
53	10.0	8.0	262	7.97	5.40	.54	.49	Tank Saturation
54	15.0	-	264	-	-	-	-	Irregular Waves
55	2.5	8.0	282	7.90	2.50	1.00	.89	Tank Saturation
56	2.5	9.0	284	9.00	2.70	1.08	1.24	Tank Saturation
57	2.5	10.0	286	9.98	1.20	.48	.68	
58	2.5	11.0	288	11.08	.34	.34	.58	
59	2.5	12.0	290	11.98	.30	.12	.24	
60	2.5	13.2	293	13.23	.30	.12	.29	
61	2.5	14.0	295	13.99	.80	.32	.84	
62	2.5	15.0	299	15.03	1.36	.54	1.60	
63	2.5	12.8	302	12.75	.20	.08	.18	

TABLE 4

CHRONOLOGY AND REGULAR WAVE RESULTS
MODIFIED U-TUBE STABILIZER IN OPERATION

RUN	Wave Height (feet)	Nominal Period (sec)	Video Tape Footage	Actual Period (sec)	Roll Double Amplitude (deg)	R.A.O. (Deg/Ft)	Roll/ Wave Slope	Remarks
64	-	-	306	-	-	-	-	Roll Decrement Experiment
65	2.5	8.0	311	7.97	1.40	.56	.50	
66	2.5	9.0	314	9.08	2.34	.94	1.10	
67	10.0	9.0	316	9.00	7.02	.70	.81	
68	10.0	10.0	318	9.98	7.60	.76	1.07	
69	10.0	11.0	321	11.08	6.56	.66	1.14	
70	10.0	12.0	323	12.06	4.26	.43	.86	
71	10.0	13.2	325	13.30	3.28	.33	.79	
72	10.0	14.0	328	14.06	4.44	.44	1.17	
73	10.0	15.0	331	15.10	5.60	.56	1.66	
74	10.0	12.8	333	12.82	2.84	.28	.64	
75	10.0	11.5	336	11.50	5.70	.57	1.06	
76	15.0	-	340	-	-	-	-	Irregular Waves

Considering Table 1 for the un-stabilized case, attempts were made to run 16 and 17 second waves but the wave machine did not co-operate and these periods were given up. Some fiddling was necessary to get a good 15 second wave run, Run 5, and this was established as the longest regular wave in the test program. (In the video tapes for Runs 3 and 4 no reasonably steady rolling is to be noted.) Runs 5 through 15 in Table 1 involve a march down the wave period range. It may be noted that the maximum roll double amplitude was 52.2^{o} at a nominal wave period of 12.4 seconds. This would have been nearly enough to roll the model deck under had the model sheer been cut at main deck level. The next step in the program was to produce data for larger and smaller wave heights at the period of maximum response. Run 16 involves halving the wave height at the nominal 12.4 second period. The fact that the R.A.O. decreased for this run relative to that for Run 10 (10' wave, 12.4 second period) suggested that the model might be rolled under if the wave height was increased significantly beyond 10 feet, and thus the second of the two additional wave heights was chosen by halving again (Run 17, 2.5 foot height, 12.4 second period). The next part of the program involved obtaining a run in reasonably severe irregular waves.* The data for the first attempt (Run 18) was partly lost and the run was repeated (Run 19). At the conclusion of these runs it was clear that no increase in the severity of the model irregular waves was prudent since some water was shipped over the model deck edge near the 01-level. At this point in the program the regular and irregular wave parameters for the succeeding tests had been established. However, the fact that the roll R.A.O. decreased with wave height (Runs 10,16,17) deserved some further attention. Accordingly, a repeat of the run where maximum roll had been observed was made, and then a short series of regular wave runs with 2.5 foot height was made to define the rolling peak for this wave height.

The sequence of events for the basic U-tube case, Table 2 followed the pattern established in the un-stabilized case, and nothing unexpected transpired.

In the case of the free surface stabilizer, Table 3, the same basic pattern was followed through Run 54, with the exception that two regular wave periods were added because tank saturation was observed at the low end of the period range. In the irregular wave Run 54 a great deal of

*Wave heights in the tables refer to significant heights.

tank saturation was observed. The fluid in the free surface tank impacted the tank covers port and starboard sufficiently violently as to squirt water out of the tank vents, Figure 1. In this run, of about 15 minutes duration full scale, the equivalent of 6 inches of water (1/8 of the total) was lost from the tank.

With the completion of Run 54 the planned work was complete but some time remained in the budget. There was not enough time to change to a new ship loading condition and repeat the basic test plan, but there was enough to try to learn a little more about each stabilizer, and this was the course taken.

Visual observations of the free surface tank suggested that it might be under damped for small wave heights. Accordingly, Run 55 through 63, Table 3, were undertaken to define the stabilized response in 2.5 foot regular waves.

In consultation with the designers of the U-tube tank it was decided that the most useful thing to do in the case of the U-tube was to see what influence a reduction of tank damping would have upon stabilized response. Accordingly the "Basic" U-tube crossover was altered to the "Modified" crossover, Figure 4, and a slightly abbreviated test sequence was run as indicated in Table 4.

TEST RESULTS

Roll Decrement Experiments

Figure 6 indicates the results of the four roll decrement experiments:

Run 1 No stabilizer
Run 24 Basic U-tube
Run 39 Free Surface tank
Run 64 Modified U-tube

In each case points plotted on full cycles are starboard side down amplitudes, points plotted on half cycles are port side down. These amplitudes were measured with respect to instrumentation zero and some assymetry is shown to be present.

The concave upward trend for Run 1 (No stabilizer) is unusual, as is the "jog" in the trend for the free surface stabilizer, Run 39. The gross difference between the stabilized and unstabilized cases is however as expected.

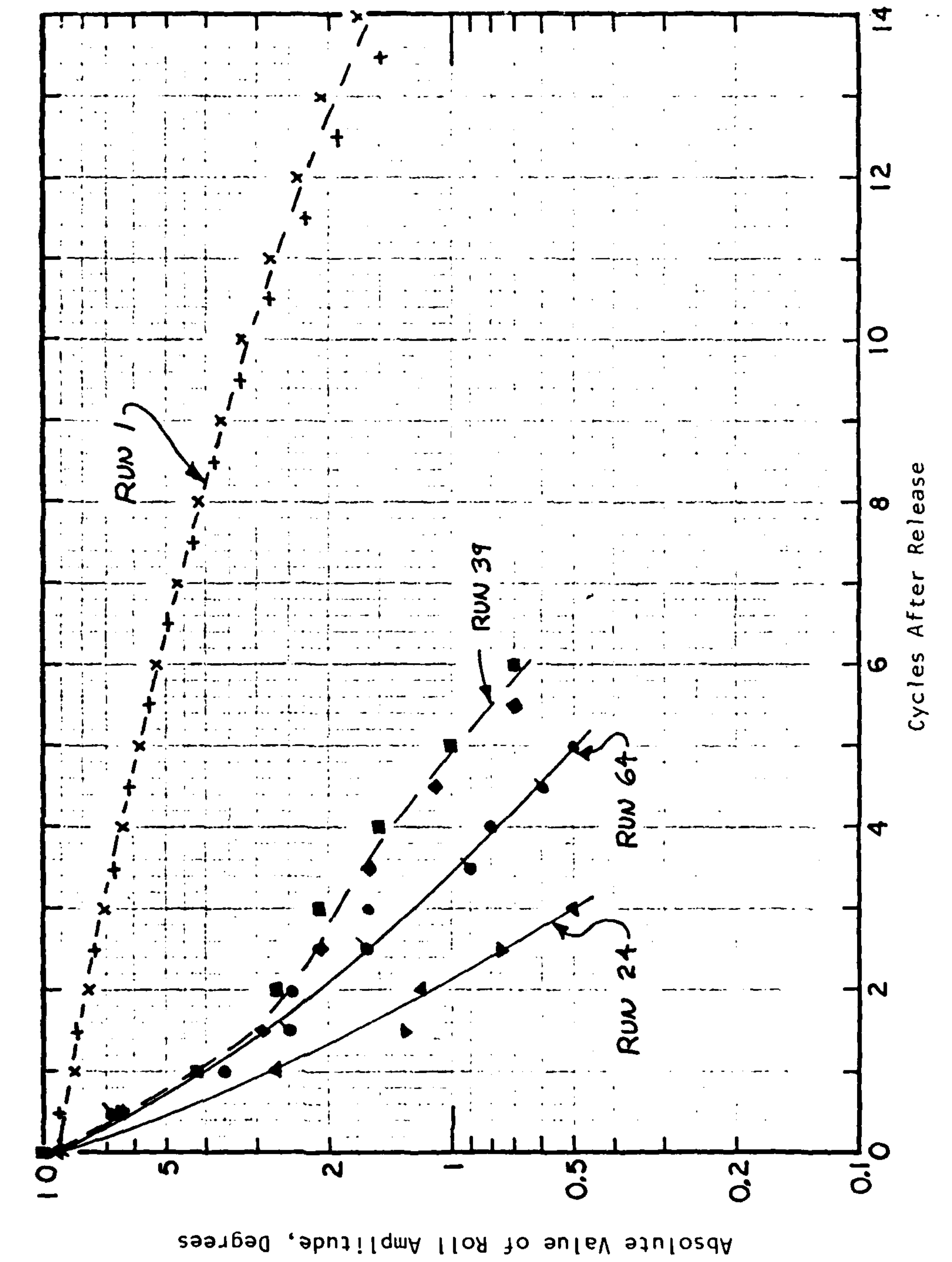

FIGURE 6 RESULTS OF THE ROLL DECREMENT EXPERIMENTS

Regular Wave Test Results

Figure 7 contains all the roll response operator data in Tables 1 through 4 plotted against wave period.

The data for the no stabilizer case describes a ship which is extremely lightly damped in roll. The response in 2.5 foot waves is extra-ordinary as a multiple of wave slope. The shift in the peak response for 10 foot waves to shorter than nominal resonant periods is a "hardening" characteristic, which is believable considering the present ship geometry.

All stabilizer configurations effectively reduce resonant rolling. In the 10 foot waves between 86 and 95% roll reductions are achieved. On this criterion the free surface tank is better than the modified U-tube by a very small margin, and both are marginally better than the basic U-tube.

The data shown for the free surface tank in 2.5 foot waves appears very close in character to the classical case of an under damped vibration absorber. Practically perfect stabilization at resonance is shown, as well as significant magnification at lower periods and a suggestion that magnification would also occur at periods longer than those tested. The two points for the modified U-tube at 2.5 foot wave height suggest that this stabilizer might also be slightly under damped in lower waves.

Irregular Wave Results

Roll double amplitudes were measured from the four irregular wave response records according to the zero crossing convention. Averages, and averages of third and tenth highest double amplitudes were computed. The results are summarized in Table 5. The irregular wave program used to obtain these data produces a reasonable approximation to a fully developed wind generated sea spectrum (the ITTC single parameter or the Pierson-Moskowitz). Thus for 15 foot significant waves there is some wave variance at nominal roll resonance frequencies, but not much (the modal period is just short of 11 seconds). Nevertheless, between 40 and 50% roll reduction was achieved by the various stabilizers. The free surface and modified U-tube were equal in this respect, and better than the basic U-tube.

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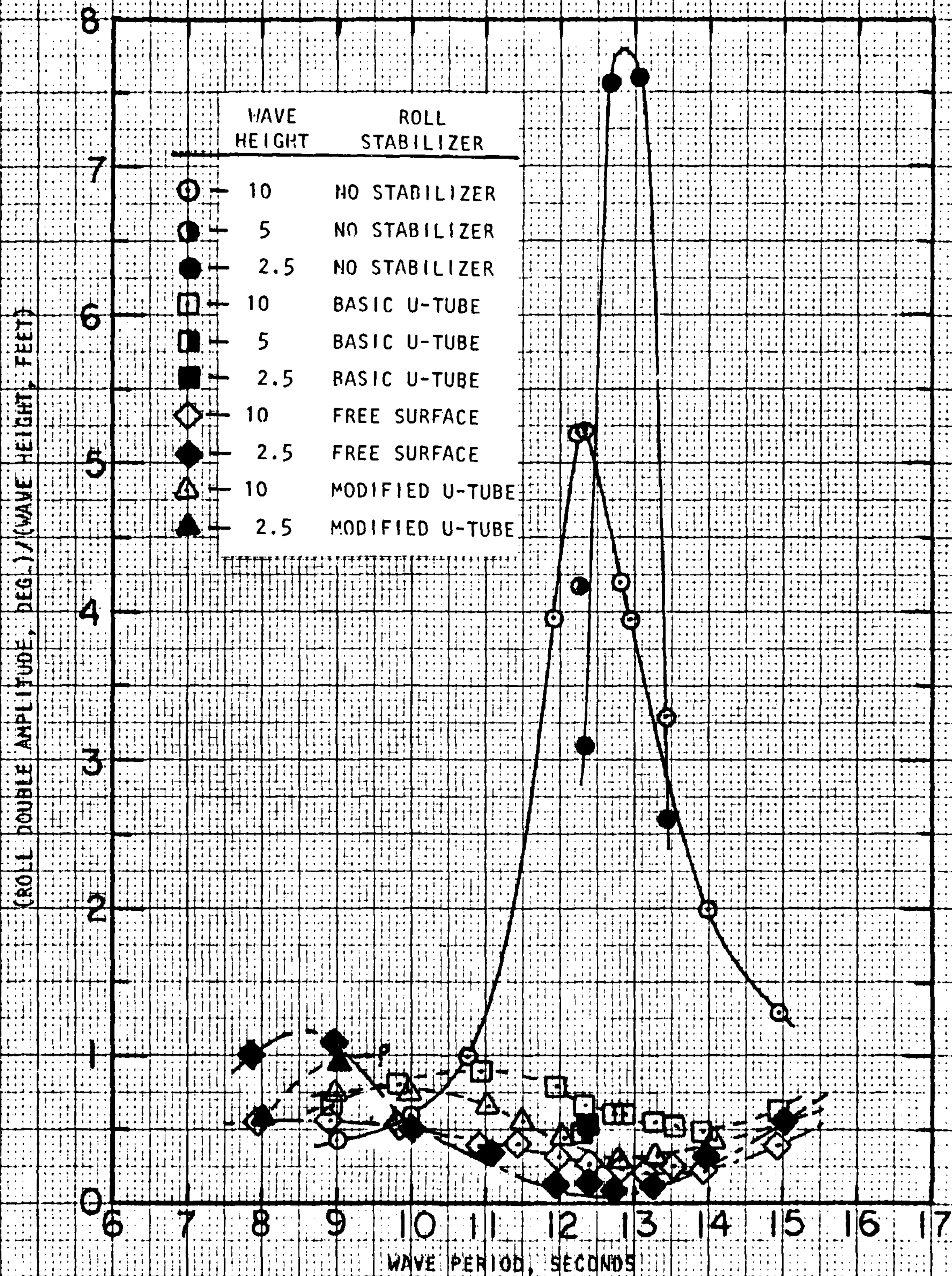

FIGURE 7 REGULAR WAVE TEST RESULTS

TABLE 5

IRREGULAR WAVE TEST RESULTS

Stabilizer Condition	No Stabilizer	Basic U-Tube	Free-Surface Tank	Modified U-Tube
Run Number	19	38	54	76
Number of Rolls	78	82	80	79
Average Double Amplitude, Deg.	12.5	7.6	6.1	6.0
Average of Third Highest Double Amplitudes, Deg.	20.4	12.0	9.7	10.6
Average of Tenth Highest Double Amplitudes, Deg.	26.0	15.8	12.9	14.0
The Maximum Double Amplitude, Deg.	32.0	18.0	16.2	15.5

COMMENTARY

On the basis of gross performance the present experiments suggest no overwhelming advantage of one stabilizer type over the other. This undoubtedly comes about in part because the ship apparently is severely underdamped in rolling.

Neither of the U-tube variants were close to saturation during any of the experiments. However, saturation of the free surface tank was evident, and quite violent in the irregular wave trial. Though saturation evidently did not badly degrade the performance of the free surface tank during the experiments, the observations suggested that degradation of effectiveness of this stabilizer might well set in for wave conditions not too much more severe than those modelled.

The violence with which the characteristic bore of the free surface tank impacted the tank ends and overhead suggests that the tank as tested could pose a habitability (noise) problem. Because the results suggest that this tank could be more heavily damped without great penalty, the conventional row of stanchions separating wings and crossover might be considered. These have the effect of breaking up the bore and "civilizing" the flow in the wings so that impacts are reduced and saturation takes place more gracefully.

In the context of producing the best design compromise, the results suggest that too much structure was mandated for inclusion into the U-tube crossover. Somewhat less tank damping should be beneficial to performance of the basic U-tube design and thus consideration should be given to relocation of a part of the presently designed crossover structure.

REFERENCES

1. "Preliminary Design Report for a Dual Draft Icebreaker", United States Coast Guard, Naval Engineering Division and Electronics Engineering Division, 1 November 1979.

2. "Preliminary Design of a Passive U-tube Stabilizer for the United States Coast Guard Dual Draft Icebreaker", Report CG80-1, Ship Research Incorporated, September 1980.

APPENDIX C

"Bench Tests of a U-Tube Stabilizer
for the Dual Draft Icebreaker"

Ship Research Incorporated Report CG80-2
July 1981

BENCH TESTS OF
A U-TUBE STABILIZER FOR
THE DUAL DRAFT ICEBREAKER

Report Number CG80-2

July 3, 1981

Prepared for

Davidson Laboratory
Stevens Institute of Technology
Hoboken, New Jersey

BENCH TESTS OF A U-TUBE STABILIZER FOR THE COAST GUARD DUAL DRAFT ICEBREAKER

INTRODUCTION

A roll stabilizing system consisting of a single U-Tube stabilizing tank has been developed for the Coast Guard Dual Draft Icebreaker. The tank is to be used under all loading conditions. The characteristics of the tank are:

Location (frames)	127-143
Bottom of tank	01 level
Nominal water level	9.0 feet
Weight of fresh water	118 tons
Free surface loss (Δ = 6500 tons)	0.73 feet

The design of an effective antiroll tank system requires the matching of the dynamics of the tank to those of the ship. Due to the complexity of the geometry of the flow path through the tanks and the effect of the internal structure, it is difficult to predict theoretically the inertial and damping characteristics of the tank with sufficient reliability. It is therefore customary and prudent to perform tests on a scale model of the tank to determine its performance and damping properties.

The most common technique employed for this purpose uses a sinusoidally oscillated table or bench on which the tank model is mounted. The moments exerted by the tank on the driving mechanism are recorded and analyzed for various frequencies and amplitudes of excitation. This method requires expensive equipment, and the analysis of the data requires extreme care since the dynamic tares introduced by the inertias of the tank and bench are large. Although the oscillating table tests are required for free surface roll tanks, a simpler, more direct and inherently more accurate test is possible for U-tube tanks. Here, the tank is given an impulsive motion, and the time history of the water level in one leg of the tank is measured. Analysis of this time history yields directly the dynamic properties of the tank. In this way, the measurements concentrate on the fluid motion, and there is no need to deal with extraneous tares. The impulse method was therefore chosen for these tests and is described in detail below.

Objective

It is the objective of the model test program to determine the dynamic properties of the roll tank. Experience has shown that the dynamics are well characterized by the natural frequency and the damping coefficients, both linear and quadratic. Other characteristics of the roll tank, such as free surface loss, are geometric in nature and can be determined from the full scale geometry itself.

Scaling

It is desired to test a small model of the tank in order to determine its properties. It is necessary to preserve certain dynamic laws, which require the maintenance of certain non-dimensional groups, if the model is to perform exactly as the full scale tank. For precise modeling it would be necessary to preserve the Froude number, Reynolds number, Weber number and cavitation numbers. Because of the limited number of fluids available, it is not possible to preserve all of these ratios. The situation is analogous to ship model testing. Weber number (relating to surface tension) and cavitation number govern phenomena which are not important for roll tanks and, as a result, lack of preserving these parameters is not critical.

Froude scaling can be accomplished by scaling the time base in the following way:

$$t_m = t_p \sqrt{r}$$

where

t_m, t_p are the reference time bases for the model and prototype respectively,

r is the scale ratio, the ratio of a linear dimension of the model to a corresponding dimension on the prototype.

The time base scales as the square root of the scale ratio. In this case, motions in the model will occur in a shorter time than for equivalent motions in the prototype.

Reynolds scaling requires that viscous properties of model and prototype are preserved, and, thus, for a Froude-scaled model:

$$\nu_m = r^{3/2} \nu_p$$

where

ν_m, ν_p are the kinematic viscosities of the fluid used in the model and that in the prototype respectively.

That is, we need a much smaller viscosity in the model fluid than in the full scale fluid. Since it is intended to use water in the prototype, and since water has the lowest kinematic viscosity of all practical fluids, it is therefore impractical to preserve Reynolds scaling. The effect of not matching Reynolds numbers between model and prototype can be minimized by making the model as large as practical.

Two facets of the roll tank testing ameliorate the Reynolds number discrepancy. First, as long as the flow, both full scale and model scale is turbulent, then little difference occurs in such quantities as frictional drag. The tank under consideration has a considerable internal structure which tends to provide constant "tripping" of the flow to turbulent conditions in both model and prototype. Second, most of the losses in the tank occur due to sudden constrictions in the flow, in this case, in the crossover duct. It is well known that this type of loss is practically independent of Reynolds number. In conclusion, it is seen that the lack of Reynolds scaling will not produce large errors in measurement of the tank properties.

The existence of laminar flow can be detected easily. Entrance losses, exit losses and turbulent friction losses lead to quadratic tank damping. Laminar flow losses lead to linear tank damping. Thus, the linear coefficient of damping determined in these tests is a measure of the laminar flow in the model. Generally, laminar flow losses on the model are greater than the equivalent turbulent flow losses which will certainly occur in the full scale. It is sometimes appropriate, therefore, to replace the linear coefficient in the tank dynamics with an equivalent non-linear coefficient, in order to predict the full scale tank dynamics.

The model scale ratio corresponds to a time scale 0.25 times full scale time (Froude scaling) and a model Reynolds number 0.0156 times the full scale Reynolds number.

The Model

A model, geometrically similar to the full-scale tank, was constructed of plexiglas to a scale ratio of 1:16. Figures

1 and 2 show the stabilizer, including structural detail of the duct. The water level probe can be seen in the wing tank on the left. Since the structure in the wing tanks will not measurably affect the tank performance, it was not included in the model. The top of the duct is removable, to allow changes to be made to the structure within the duct, if necessary.

Test Apparatus and Procedure

The motion of the water in one leg of the U-tube was measured by means of a capacitance wave probe, which can be seen in Figures 1 and 2. An electronics package and a computerized digital recording system were used to record the water level at time intervals of 0.03 seconds for a total of 15 seconds. The capacitance probe was adjusted as much as possible for linear performance and was calibrated by setting the tank at several different known angles. The tank angle could be measured to within about 0.1 degrees.

Each test consists of the following steps. First, the model is tilted to cause the water levels in the two wings to differ. With the tank tilted, the valve on the air crossover duct (see the inboard side of the left wing tank in Figure 1) is closed. The tank is then set in a level position. The water levels in the two wings continue to differ, since the air above the water is trapped in each wing tank. The recording system is initiated. Almost immediately thereafter, the air crossover valve is opened, releasing the water. The water oscillates back and forth from one wing to the other, gradually decaying in amplitude.

The data system records the water level time history in one wing of the tank. These data are converted to tank "angle" by dividing by the distance from the center of the ship to the centroid of the water surface area in the wing tank.

Analysis

The objective of the tests is to evaluate coefficients in the equation of motion of the water in the tank. The equation of motion is of the form:

$$m\ddot{\tau} + c\dot{\tau} + b|\dot{\tau}|\dot{\tau} + k(\tau - \phi) = 0 \qquad (1)$$

where τ is the angle of the water in the tank
ϕ is the angle of the tank from the horizontal.

Defining

ω_r	$\equiv$	$\sqrt{k/m}$	resonant frequency
c_c	$\equiv$	$2\sqrt{km}$	critical damping
ζ_1	$\equiv$	c/c_c	linear damping ratio
ζ_2	$\equiv$	$b\tau_R/2m$	nondimensional quadratic damping coefficient
τ_R	$\equiv$		reference dimension in units of τ,

the equation can be written:

$$\ddot{\tau} + 2\zeta_1\omega_r\dot{\tau} + 2\zeta_2\omega_r\left|\frac{\dot{\tau}}{\omega_r\tau_R}\right|\dot{\tau} + \omega_r^2(\tau - \phi) = 0 \qquad (2)$$

The tank dynamics are defined by the values of ω_r, ζ_1 and ζ_2.

The analysis consists of finding values of ω_r, ζ_1 and ζ_2 which minimize the differences between the time histories of tank angle as measured in the tests from values computed from equation (2) in simulations of the tests. The approach is to estimate the values, and then to improve the estimates by an iterative least-squares-fit procedure. The parameters evaluated in the analysis include not only ω_r, ζ_1 and ζ_2, but also the initial tank angle τ_o, the release time t_o, and the final (at rest) angle ϕ, for each test.

The least-squares-fit procedure is as follows. We have test values of the tank angle for several tests, measured at a large number of times (500) during each test. The angles are:

$$\hat{\tau}_i \quad ; \quad i = 1,2,\ldots\ldots,I$$

where I is the total number of measurements from all tests. The theoretical tank angles are functions of the input parameters and, of course, time, which is omitted for brevity:

$$\tau_i = \tau_i(\vec{p}) \; ; \quad i = 1,2,\ldots\ldots,I$$

where

$$\vec{p} = (\omega_r, \zeta_1, \zeta_2, \tau_{o1}, t_{o1}, \phi_1, \ldots\ldots, \phi_N)$$

N is the number of tests. To find the best values of the parameters $\vec{p}$, the function is linearized about the current estimate, $\vec{p}_o$:

$$\tau_i(\vec{p}) \cong \tau_i(\vec{p}_o) + \sum_{j=1}^{J} d_{ij}\,\Delta p_j \tag{3}$$

where d_{ij} is the partial derivative of $\tau_i(\vec{p})$ with respect to p_j, the jth parameter, evaluated at $\vec{p} = \vec{p}_o$

$\vec{\Delta p}$ are small variations of $\vec{p}$ in the vicinity of $\vec{p}_o$

J is the number of parameters (3 + 3N).

Comparing the data to the linearized representation of the theory, the error is

$$\epsilon_i = \hat{\tau}_i - \tau_i(\vec{p}_o) - \sum_{j+1}^{J} d_{ij}\,\Delta p_j \tag{4}$$

To minimize the sum of the squares of all of the errors, we set to zero the derivative of this sum with respect to each of the deviations $(\vec{\Delta p})$ of the parameters from the current estimate:

$$\frac{\partial}{\partial \Delta p_k} \sum_{i=1}^{I} \left[\hat{\tau}_i - \tau_i(\vec{p}_o) - \sum_{j=1}^{J} d_{ij}\,\Delta p_j \right]^2 = 0; \qquad k = 1,2,\ldots J \tag{5}$$

Taking the derivatives and rearranging, the equations become:

$$\sum_{j=1}^{J} \sum_{i=1}^{I} d_{ij} d_{ik} \; \Delta p_j \quad = \quad \sum_{i=1}^{I} d_{ik} \; \epsilon_{oi} \; ; \; k=1,2,..,J \qquad (6)$$

where $\epsilon_{oi} = \hat{\tau}_i - \tau_i(\vec{p}_o)$, the current error.

Given the initial estimate for the parameters, $\vec{p}_o$, the theoretical values for all data points are computed by equation (2). Then equations (6) are solved to yield the incremental changes in the parameters to best fit the test data. The process is repeated until no further change is observed in the parameters. The solution converges rapidly, each set of incremental changes an order of magnitude smaller than the prior set.

The derivatives of the theoretical function are evaluated by two techniques. First, some derivatives can be evaluated simply in closed form. For example, the solution to equation (2) is a function of the product $\omega_r (t - t_o)$, where t is time and t_o is the release time. Therefore, the derivative with respect to ω_r is

$$\frac{\partial \tau}{\partial \omega_r} = \frac{\partial \tau}{\partial t} (t - t_o) / \omega_r$$

Since ω_r is parameter 1, $d_{i1} = \dot{\tau}_i(\vec{p}_o)(t - t_o)/\omega_r$.
Also,

$$\frac{\partial \tau}{\partial t_o} = - \frac{\partial \tau}{\partial t}$$

If t_o is the kth parameter, then $d_{ik} = - \dot{\tau}_i(\vec{p}_o)$.
For those parameters whose derivatives are not easily evaluated in closed form, parallel integrations are performed with slightly perturbed values of the parameters. The derivatives are evaluated numerically:

$$d_{ij} = \left[\tau_i(\vec{p}_o + \delta p_j) - \tau_i(\vec{p}_o) \right] / \delta p_j$$

where δp_j is the perturbation of the jth parameter.

Results

The analysis of the data shows that the tank frequency is 2.163 radians per second (period 2.90 seconds), corresponding to a full scale resonant period of 11.63 seconds. The linear damping ratio is 0.0585, and the nondiemnsional quadratic damping coefficient is 0.0373 (τ_R = 1.0°). The root mean square error of the fit is 0.14 degrees.

The data and the correlated theory are compared in Figures 3 through 10. Each symbol represents the average of three consecutive points. (Since each test produced 500 data samples, not all points could be individually displayed.) The plots show nine seconds worth of the 15-second tests, 60% of the data.

It is interesting to note the qualitative differences in the tests depending on the sign of the initial angle. Those tests starting with a positive angle start with the water high in the wing containing the water level probe. The water flows smoothly out of the wing tank. Those tests starting with a negative angle start with the water low in the wing containing the probe. The water initially rushing out of the duct into the wing is very turbulent, and high frequency standing waves are generated. These disturbances cause the measurements in these tests to be relatively "noisy".

Tank Modifications

During testing of the ship model and stabilizer at Davidson Laboratory, it became evident that a lower resonant period and less damping would improve the stabilizer. Davidson Laboratory recommended removing as much structure as possible from the crossover duct. Ship Research Incorporated agrees with that recommendation. Since that time, the Coast Guard has agreed to remove the stiffeners from the top of the crossover duct and from the transverse floor in the duct.

We have not conducted full bench tests on the modified configuration. Instead, we have estimated on the basis of semi-empirical formulas the effects of these changes on the stabilizer dynamic characteristics.

These estimates are supported by uninstrumented bench tests. For these tests the top of the duct was removed, turned over and installed upside down, leaving the top inside of the duct clear of structure. The resonant period was measured by timing 20 cycles of oscillation. The damping estimate was confirmed by observing the first minimum water level for several tests initiated at a high angle. A computer simulation of the test matched the observed result.

The estimates of the modified stabilizer characteristics, based on the results of the fully instrumented bench tests, and modified on the basis of semi-empirical formulas and uninstrumented bench tests, are as follows:

Resonant period	10.8 seconds
Linear damping ratio	0.0585
Nondimensional quadratic damping coefficient	0.0193

These values are nearly optimum for this stabilizer.

Tank Responses and Damping

Using the dynamic representation of the tank, the response and equivalent linear damping ratios of the tank to sinusoidal motion at resonance were determined. The results are given in Table 1 for the range of amplitudes from 2° to 12°. These responses are practically optimum for this tank.

Input Amplitude	Response Amplitude	Magnification	Equivalent Linear Damping
2.0	6.23	3.11	0.161
4.0	9.41	2.35	0.213
6.0	11.86	1.98	0.253
8.0	13.94	1.74	0.287
10.0	15.78	1.58	0.317
12.0	17.44	1.45	0.344

Table 1 - Equivalent Linear Damping Characteristics

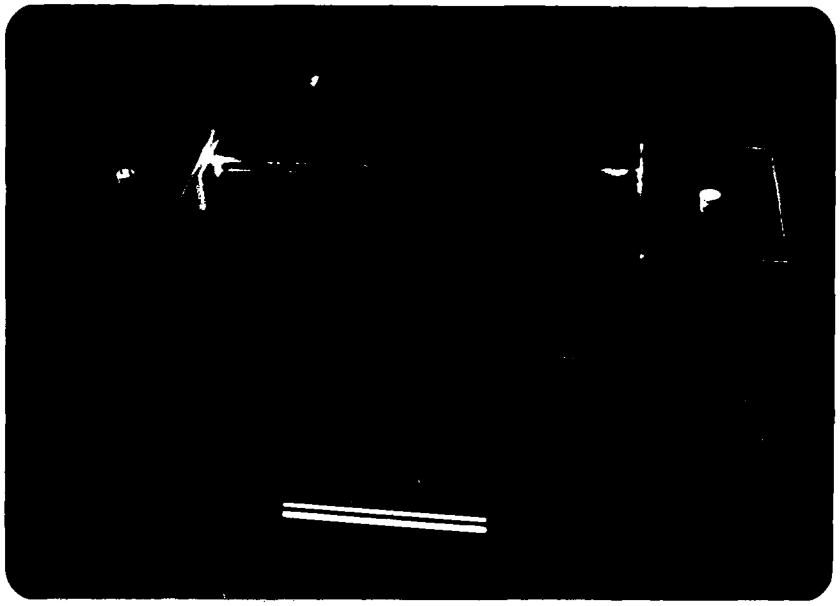

Figure 1 - Overall View

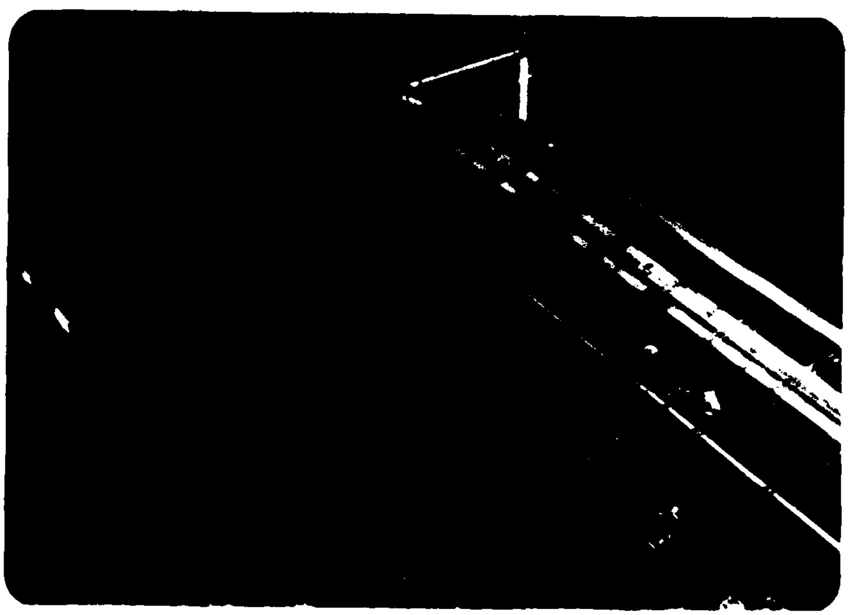

Figure 2 - Details of Duct Structure

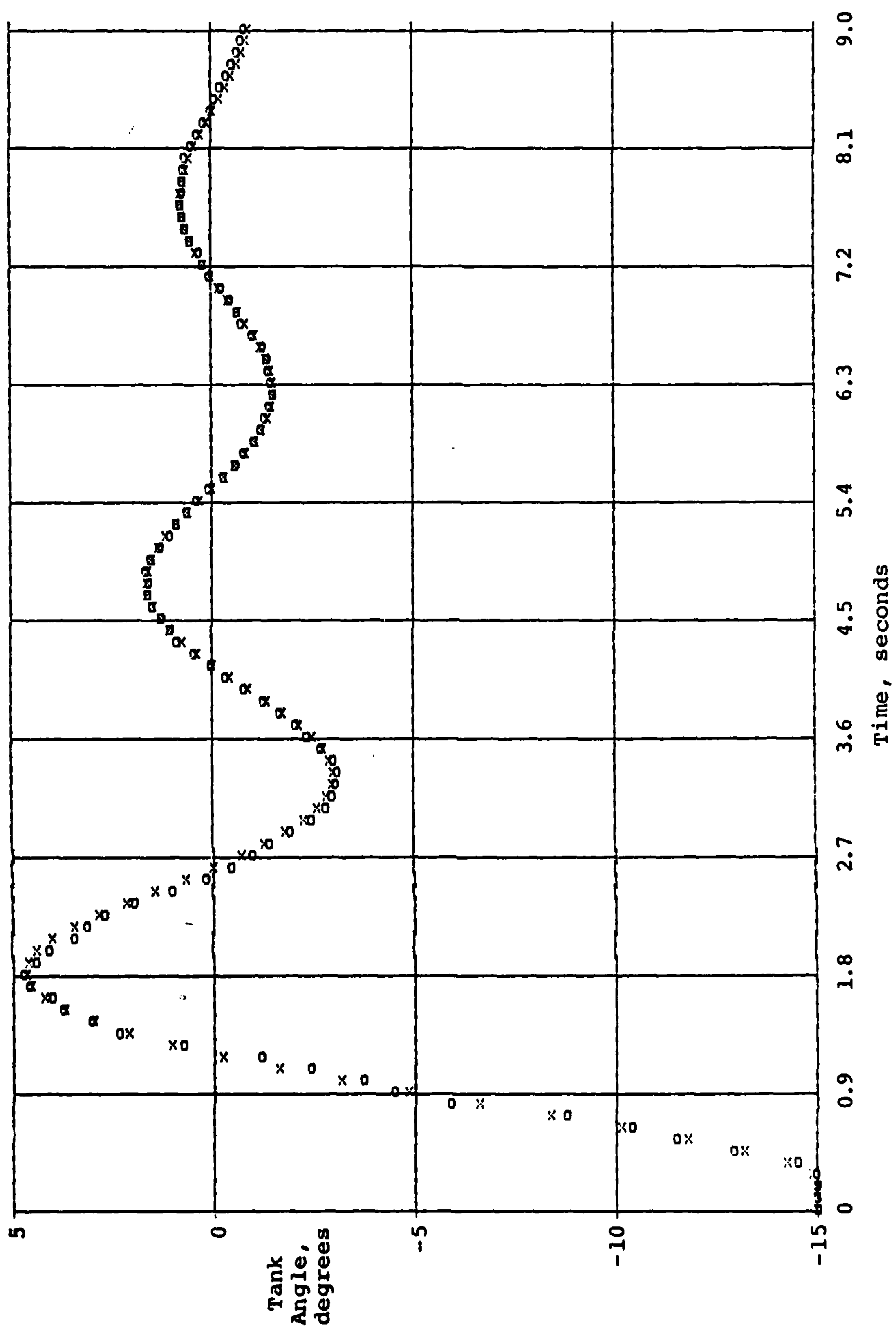

Figure 3. TIME HISTORY OF TANK ANGLE, TEST 100. Test data (o) vs. correlated theory (x)

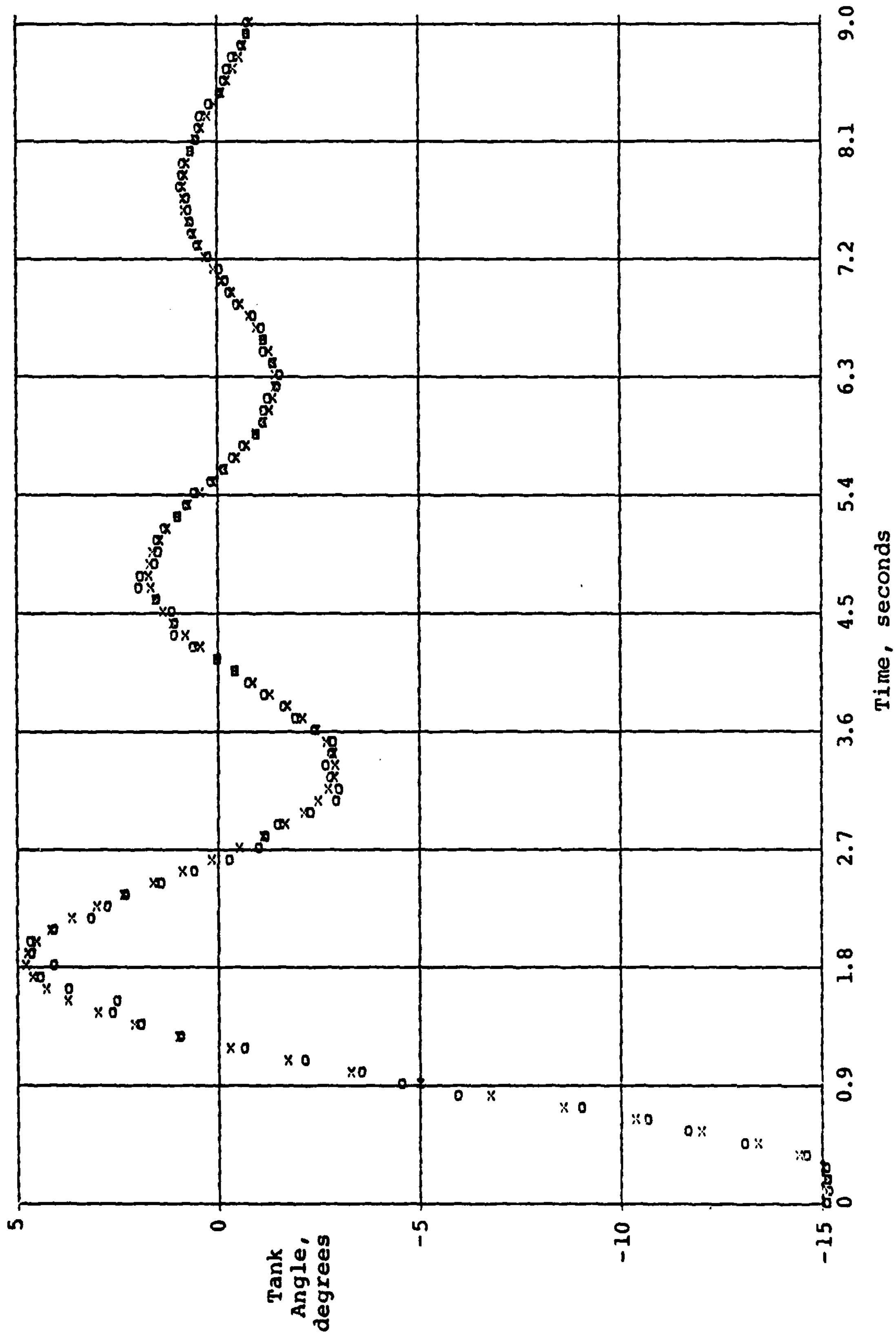

Figure 4. TIME HISTORY OF TANK ANGLE, TEST 101. Test data (o) vs. correlated theory (x)

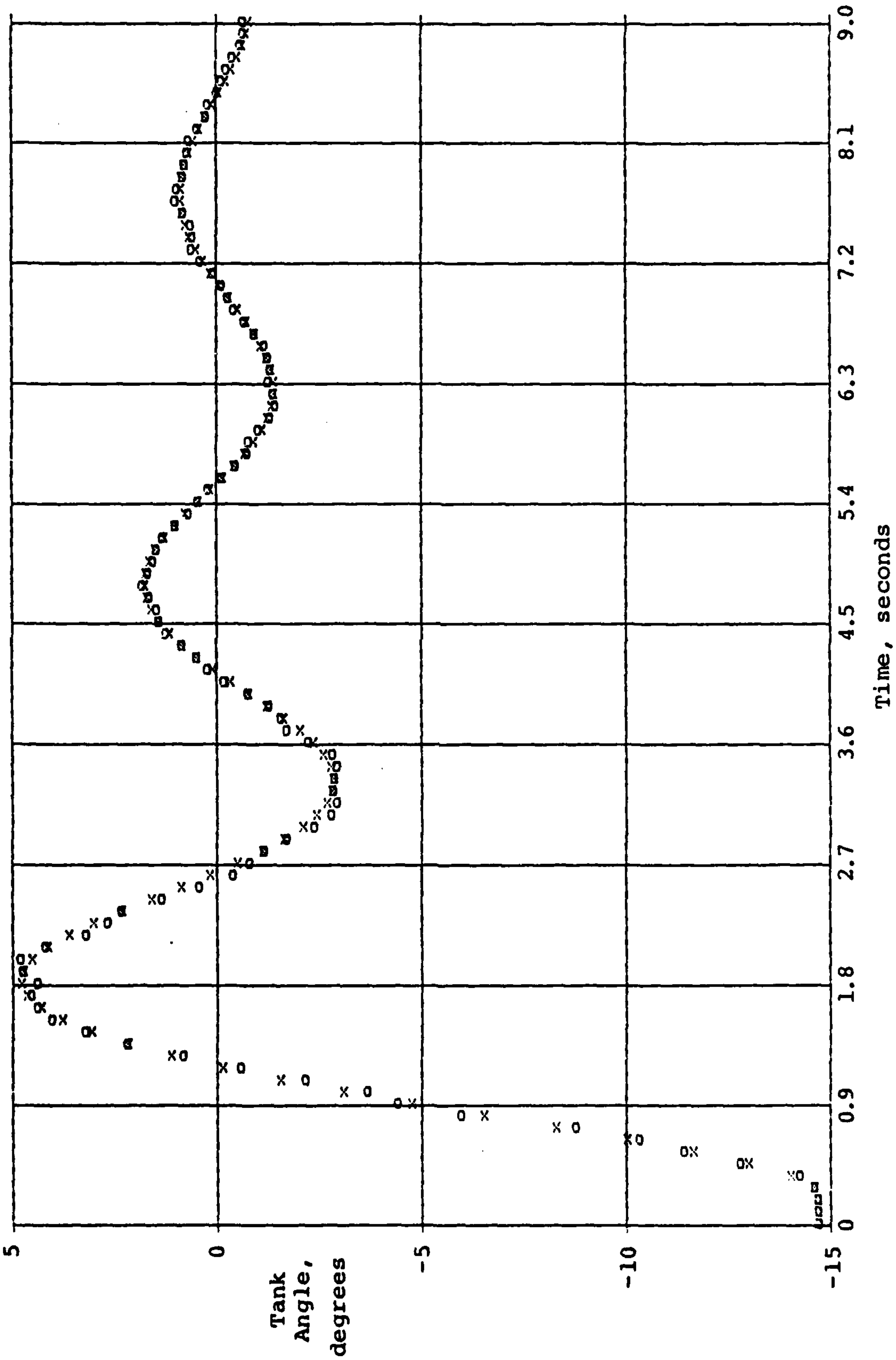

Figure 5. TIME HISTORY OF TANK ANGLE, TEST 102. Test data (o) vs. correlated theory (x)

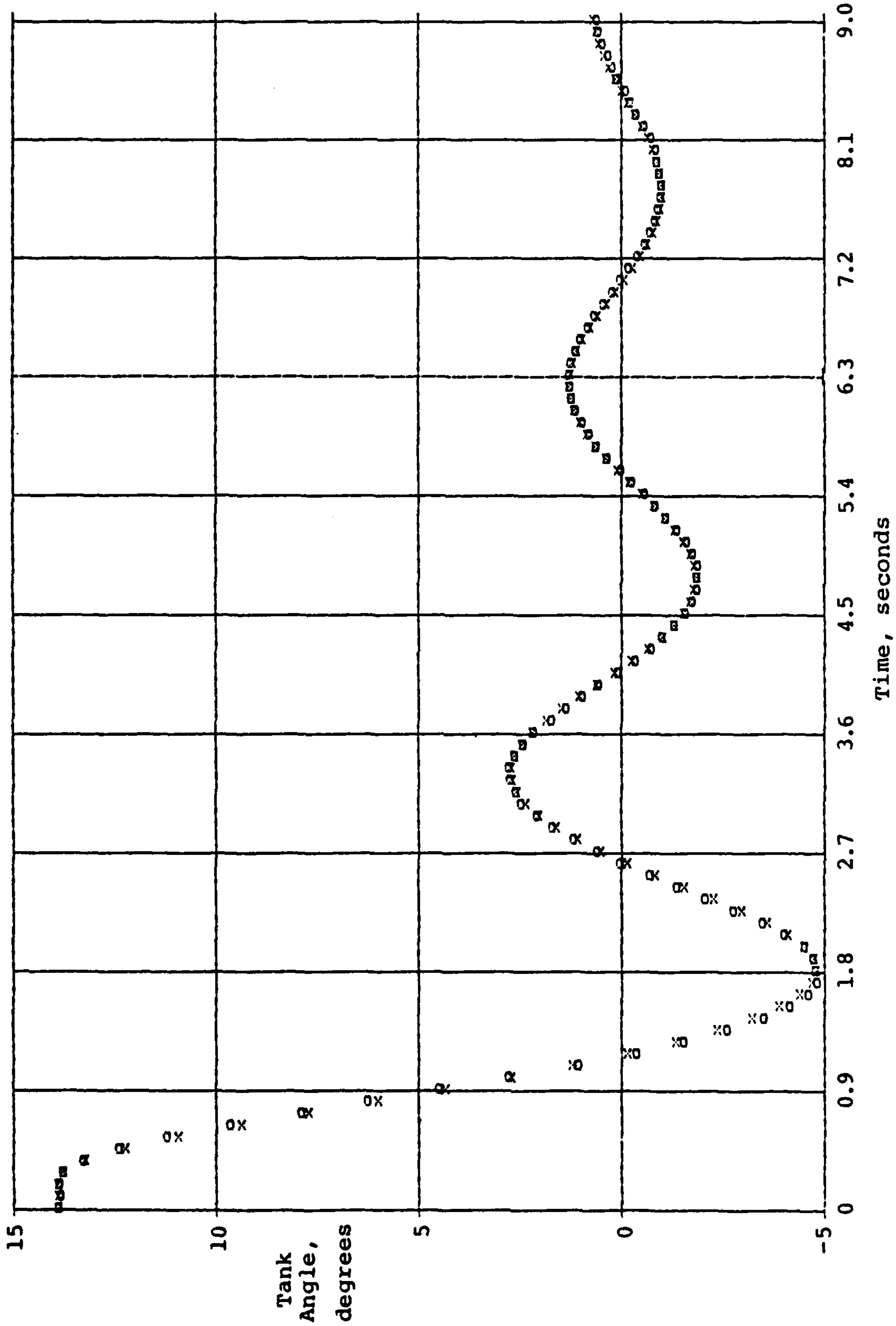

Figure 6. TIME HISTORY OF TANK ANGLE, TEST 103. Test data (o) vs. correlated theory (x)

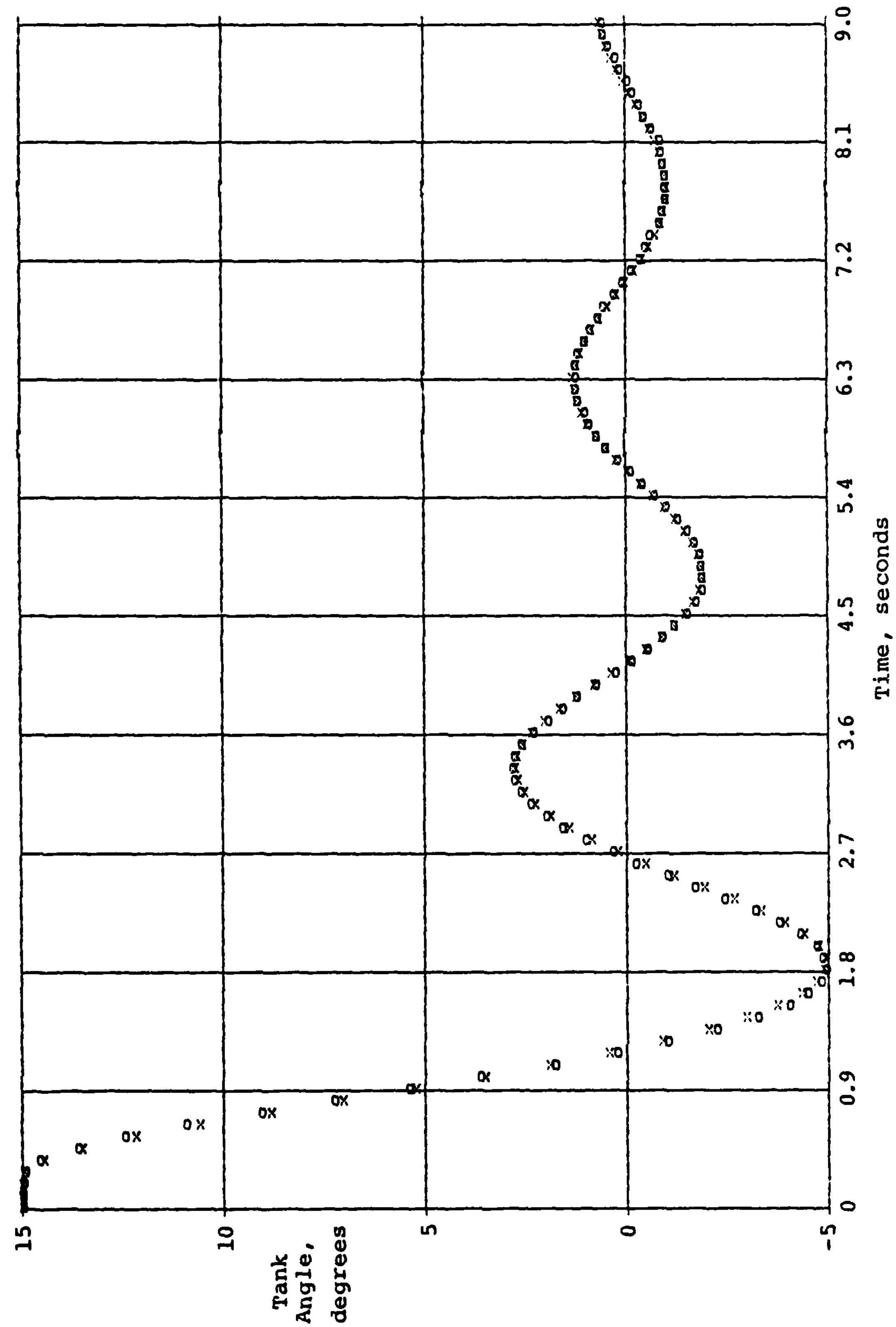

Figure 7. TIME HISTORY OF TANK ANGLE, TEST 104. Test data (o) vs. correlated theory (x)

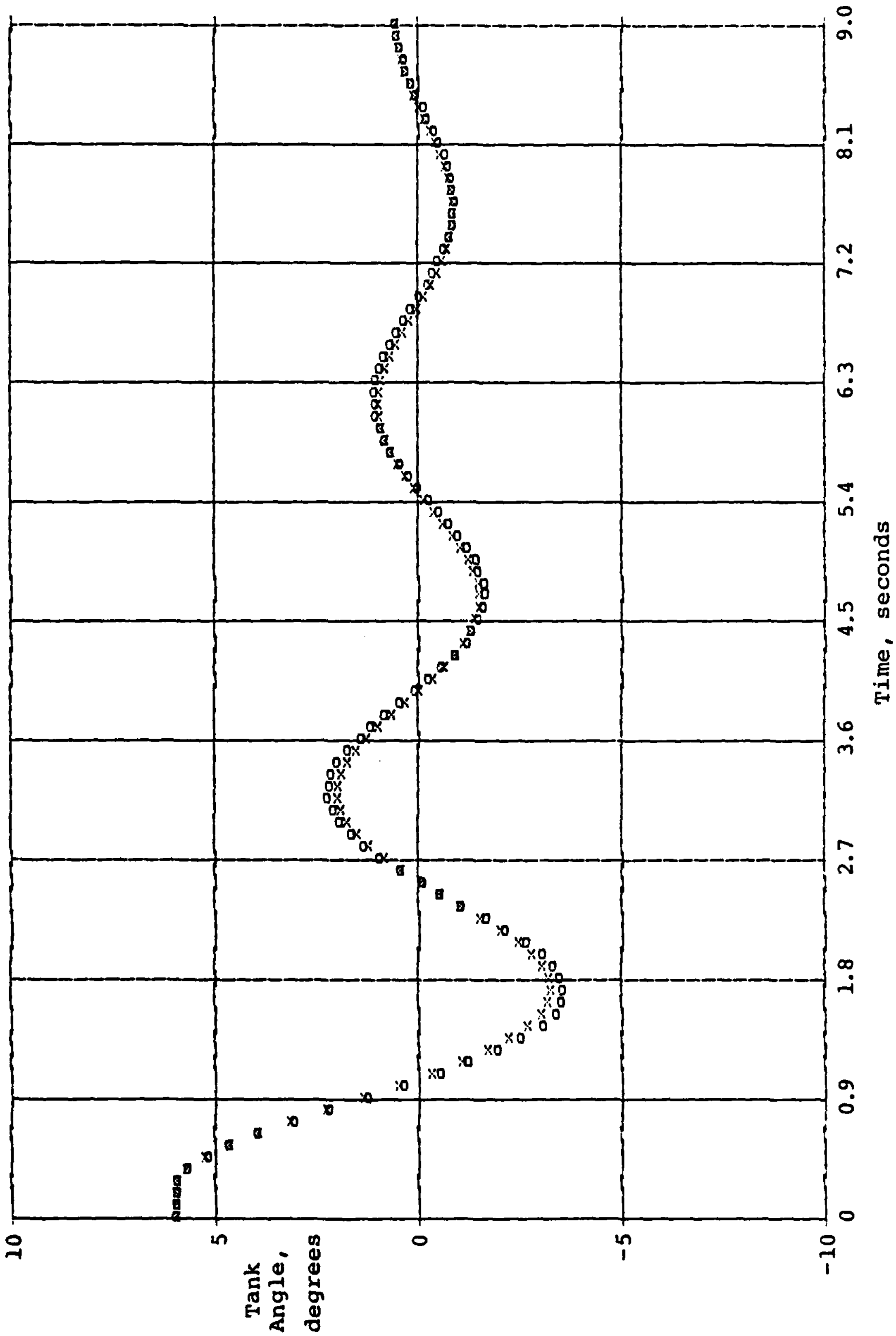

Figure 8. TIME HISTORY OF TANK ANGLE, TEST 105. Test data (o) vs. correlated theory (x)

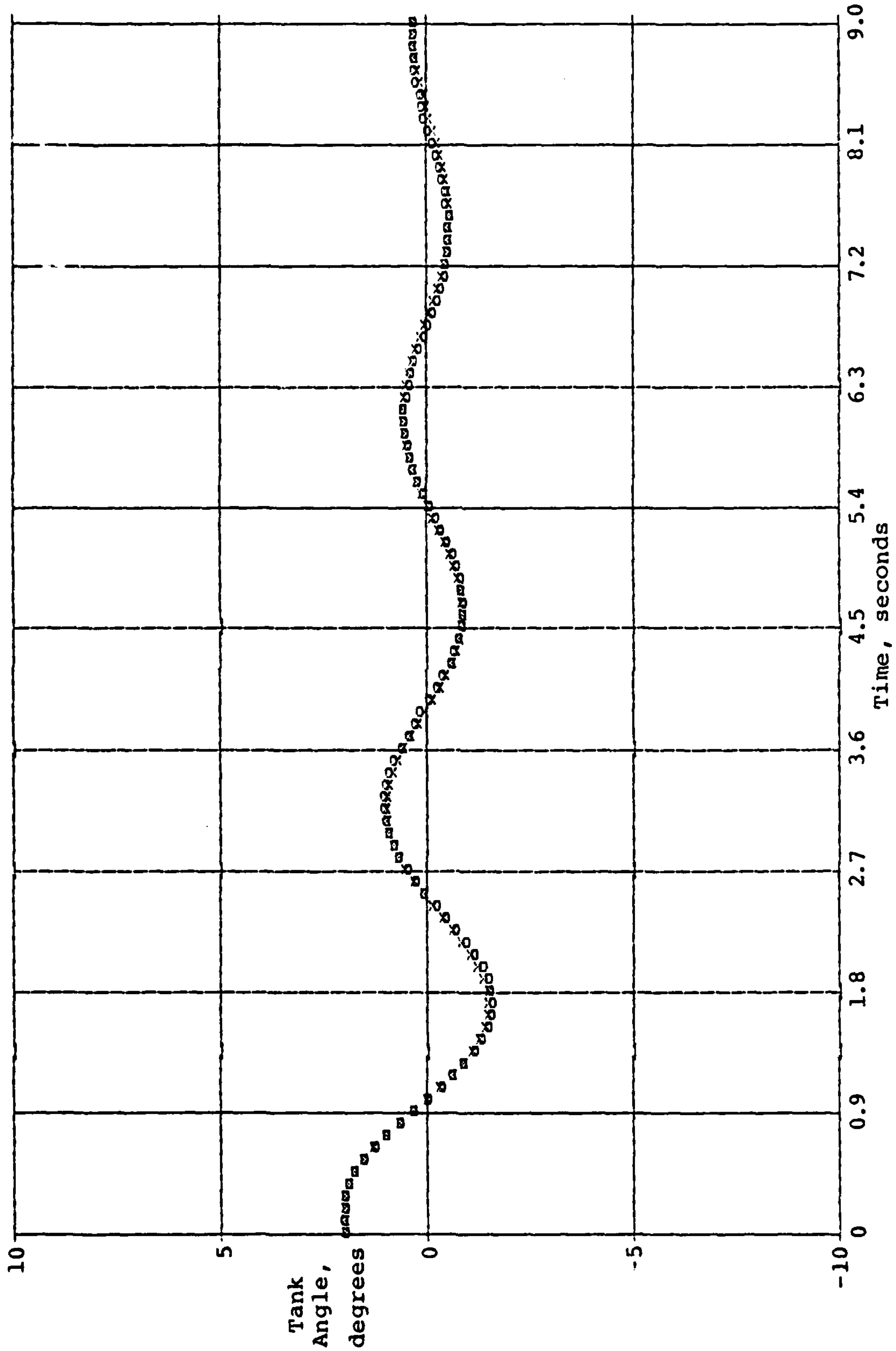

Figure 9. TIME HISTORY OF TANK ANGLE, TEST 106. Test data (o) vs. correlated theory (x)

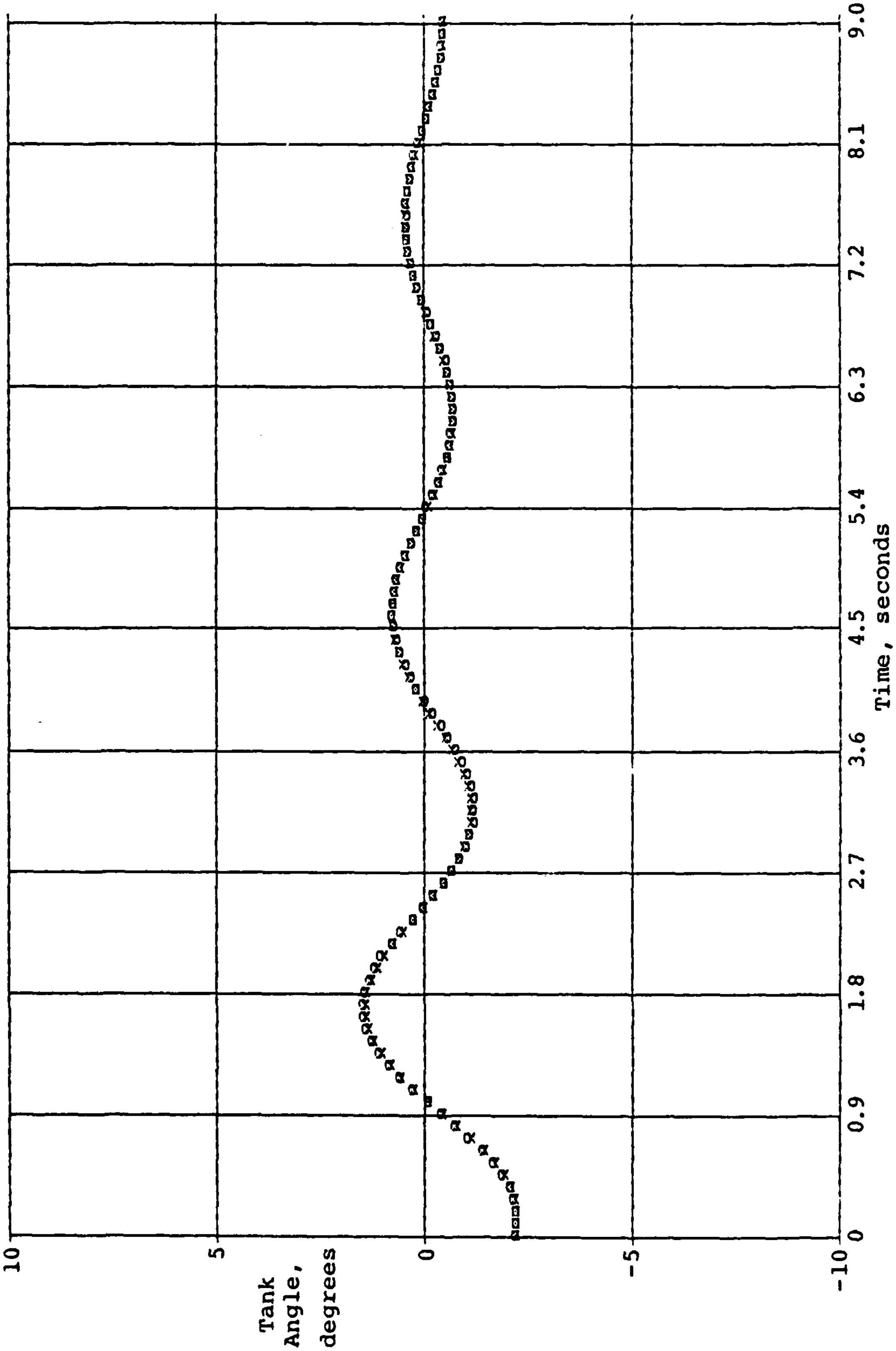

Figure 10. TIME HISTORY OF TANK ANGLE, TEST 107. Test data (o) vs. correlated theory (x)

APPENDIX D

"Design and Analysis of a Passive
Stabilizer for the Coast Guard
Dual Draft Icebreaker"

Ship Research Incorporated Report CG80-3
July 1981

DESIGN AND ANALYSIS OF A PASSIVE STABILIZER FOR THE COAST GUARD DUAL DRAFT ICEBREAKER

Report Number CG80-3

July 3, 1981

Prepared for

Davidson Laboratory
Stevens Institute of Technology
Hoboken, New Jersey

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INTRODUCTION AND SUMMARY

A passive U-tube antiroll stabilizer has been designed for the U. S. Coast Guard Dual Draft Icebreaker. In this report the design process for the stabilizer is described. An analysis of the ship performance with and without the stabilizer is presented. Some of the design details are discussed.

The stabilizer as designed is virtually optimum for this ship. The roll reductions achieved are in the range of 50 to 60 percent at cruise speed in realistic short-crested seas. Much higher reductions may be achieved in swells. The excellent performance of the stabilizer may be attributed to the intelligent allocation of adequate space for the stabilizer at an ideal location on the ship early in the preliminary design process.

DESIGN CONSIDERATIONS

In the design of a passive stabilizer system, several factors are considered. These factors are discussed in the following paragraphs.

1. Operational Requirements. It is required to have excellent stabilization in the primary operating condition and as good stabilization as possible in other operating conditions.

2. Tank Dynamics. For excellent stabilization, an anti-roll tank must have several characteristics. The free surface loss due to the tank should be 20 to 35% of the uncorrected GM. For most ships the natural frequency of the tank should be about 5% larger than the ship's roll natural frequency. At this tank natural frequency the roll motion of the ship at roll resonance is minimized. Consequently, for most ships the rolling motions while in transit in a quartering sea are most effectively reduced this this criterion. In any case, the damping of an antiroll tank should be between 20% and 50% critical damping.

3. Tank Location. To avoid excessive yaw coupling, the tank should be located near amidships. To be most effective, the tank should be located high in the ship.

4. Tank Height and Water Level. The internal height of the tank should be sufficient to preclude slamming of the water in the tank against the tank tops when the ship undergoes large motion. This generally requires a tank height-to-beam ratio of about 0.25 or greater. It is optimal to have the water level at about one-half the working height, since this gives the tank its largest roll moment capability.

5. Air Ducts. In most cases it is necessary to provide crossover pipes or ducts to carry the flow of air between the tops of the wing tanks of the U-tube. These pipes must be large enough in cross section to avoid sonic speeds under practical operating conditions. The pipes are connected to the wing tanks slightly below the wing tank tops. This geometry provides a pocket of air above the crossover pipe and thereby cushions any slamming of the water against the tank tops.

6. General Arrangements. In all cases the design of the system is constrained by the available spaces within the ship. Ideally the tank should consume a minimum amount of valuable space within the ship, and should have a minimum impact on ship operations.

7. Static Stability. In no case may the stabilizer reduce the ship's static stability below the required minimum.

8. Emergency Dumping. The stabilizer reduces the static stability of the ship. It is desirable to have the capability to dump the water from the stabilizer to maximize the static stability in an emergency.

DESIGN CHRONOLOGY

Preliminary Design

The preliminary design of a stabilizer usually consists of the following steps. Late in the design process, the ship designed or owner realizes that a roll stabilization system is needed. The stabilizer designer then negotiates with the ship designer for possible locations of the stabilizer on the ship. In each of these locations, a candidate stabilizer configuration is designed to minimize the roll motions of the ship. The candidate configurations are evaluated in terms of roll reductions achieved, weight of water required, loss of ship stability, and impact on arrangements and ship structure. The ship designer and/or owner then select(s) the configuration which represents the best compromise of all of these factors.

In the case of the DDI, in contrast to the usual process, space was allocated to the roll stabilizer very early in the design process in a way which virtually guaranteed good performance of the stabilizer. The stabilizer is located very high on the ship, approximately amidships, an optimum location. The free surface loss is sufficient for good stabilization, and the volume allocated to the crossover duct has allowed optimization of the tank dynamics.

The preliminary design conducted by Ship Research Incorporated consisted simply of identifying the optimum stabilizer dynamics, characterized by the resonant period, and defining refinements in the geometry to achieve the desired dynamics. Four specific configurations were recommended. Each of these configurations represented only a slight refinement of the configuration defined by the space allocated for the stabilizer. The preliminary design report, Reference 5 included the recommendation to minimize structural members inside the crossover duct.

The Coast Guard selected the stabilizer which conformed precisely to the original space allocated to the stabilizer. The Coast Guard at that time opted to locate 6" x 4" stiffeners longitudinally on the underside of the top of the crossover duct, in order to avoid losing headroom in the space above.

Bench Tests

After the stabilizer configuration was defined, a scale model of the stabilizer was tested as described in Reference 6 A detailed plexiglass model was built to scale of 1:16. Structural members in the crossover duct were modeled accurately. Structure in the wing tanks was not included, since by reasonably careful design this structure will not affect the stabilizer performance.

Extinction tests were conducted to determine the dynamic characteristics of the stabilizer. The tests consisted of initially changing the angle of the water in the tank, setting the tank at rest, then releasing the water by opening a valve in the air crossover duct. The time history of the water motion was recorded. A computer analysis of the data produced the resonant period of the stabilizer, the linear damping coefficient, and the quadratic damping coefficient.

Comparative Model Tests

Shortly after the bench tests of the stabilizer were completed, a model of the DDI was tested in waves at Davidson Laboratory, Stevens Institute of Technology. These tests are described in Reference 7. The 1:48 model was tested unstabilized with the U-tube stabilizer and with a free surface stabilizer. The internal geometry of the small-scale U-tube stabilizer was adjusted so that the amplitudes measured in an extinction test matched as nearly as possible those measured in the larger-scale bench tests.

During the testing it became apparent that the performance of the U-tube would be improved if the damping were reduced and the period shortened somewhat. It was noted that removal of the structure in the duct could be simulated approximately by removing some of the obstructions in the crossover duct of the U-tube. During the large-scale bench tests, the resonant period of a configuration with minimal structure in the crossover duct had been observed to be about 10.7 seconds. A small scale configuration, which had approximately this period and which appeared to represent (on the basis of all of the tests leading up to the small-scale configuration) the case of no structure in the crossover duct, was installed in the ship model and tested in waves. The performance of the stabilizer was indeed improved by this change. The Davidson Laboratory report, Reference 7 recommended reducing the amount of structure in the crossover duct.

Design Modification

The Coast Guard, after reviewing other aspects of the ship design, decided to remove almost all of the structure from inside the crossover duct. The modified design includes a transverse floor athwartship the length of the duct at frame 134 and a small amount of structure at the entrances to the duct. Ship Research Incorporated has used semi-empirical theory and a crude bench test to estimate the effects of this change on the dynamic characteristics of the stabilizer.

Final Design and Analysis

Ship Research Incorporated has simulated the performance of the final design configuration of the stabilizer for a variety of ship loaidng conditions and operating environments. These calculations are described in detail in a following section.

In addition, several design details have been specified, including the size and location of the air crossover pipe, the filling system, and the emergency dumping system. These details are also described in a following section, and are specified in the final design drawing, Reference 8.

SHIP CHARACTERISTICS

Geometry and Loading Conditions

Most of the ship data used in the calculations have been extracted from the preliminary design report, Reference 2. Six loading conditions were analyzed. These are:

- Eastern Arctic, Full load
- Eastern Arctic, 50% fuel
- Great Lakes, Full load
- Great Lakes, 50% fuel
- Great Lakes, Burned out
- Model test (75% fuel)

The full load displacement and center of gravity is directly from page 79 of Reference 2. The other loadings are derived by reducing the fuel loads only. All other loads are assumed constant. The KG of the fuel is assumed to be constant. The burned out condition is, of course, unrealistic, but represents an extremely low displacement, low GM case. It is assumed that the trim is always zero.

The hydrostatic properties are from page 23 of Reference 2. The offsets were taken from the lines drawing, Reference 3.

A summary of the ship's characteristics for these loading conditions is presented in Table 1.

Roll Dynamics

The ship roll resonant period is estimated by the following empirical formula:

$$T = 0.4B/\sqrt{GM}$$

where T is the resonant period in seconds

B is the beam

GM is the metacentric height uncorrected for free surface losses

With the information available at the current stage of the design, there is no method for computing roll resonant period which is any more reliable than this empirical formula. The roll damping ratio is estimated at 0.025 for the case of no forward way, and 0.04 for the case of 12 knots forward way. These values have not been computed, but are estimates based on experience with similar hulls. It is important to understand that roll damping is usually quadratic (the roll moment is proportional to roll rate squared), while a damping ratio applies only to linear damping (roll moment proportional to roll rate). In a linearized analysis, the quadratic damping must be represented by an equivalent linear damping, that is, a linear damping that dissipates the same amount of energy as the quadratic damping. The equivalent linear damping increases with increasing ship motions. The linear damping used in this analysis, however, is constant. Therefore, small roll motions may be underpredicted while large roll motions may be overpredicted.

General Arrangements

The general arrangements used in this study, in particular the space allocated to the stabilizer, are from arrangements drawings, Reference 4, dated 7/1/80.

STABILIZER CHARACTERISTICS

The stabilizer consists of two wing tanks, a crossover duct connecting the bottoms of the tanks, and an air crossover pipe connecting the tops of the tanks. A schematic of the tank geometry is presented in Figure 1. There is a minimal amount of structure within the tank. The recommended water level when the tank is operating is 9.5 feet.

On the basis of the bench tests, augmented by semi-empirical theory, the dynamic characteristics of the tank are as follows:

Resonant period	= 10.8 seconds
Linear damping ratio	= 0.0585
Nondimensional quadratic damping coefficient (τ_R = 1.0 degrees)	= 0.0193

These parameters are defined in Reference 6, the bench test report.

In a linear analysis of the system, we need to replace the quadratic damping of the system with an equivalent amount of linear damping. The criterion for equivalency is that the average rate of energy dissipation over a long period of time be the same. It can be shown that the equivalent linear damping ratio in a Gaussian seaway is:

$$\zeta_e = \sqrt{\frac{8}{\pi}}\left(\frac{\sigma_{\dot{\tau}}}{\tau_R \omega_r}\right)\zeta_2 + \zeta_1$$

where ζ_1 is the linear damping ratio

ζ_2 is the nondimensional quadratic damping coefficient

$\sigma_{\dot{\tau}}$ is the standard deviation of the rate of change of the tank angle

τ_R is the reference dimension in units of τ

ω_r is the resonant frequency of the tank

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SUMMARY REPORT: DESIGN AND DEVELOPMENT OF U-TUBE STABILIZER TAN--ETC(U)
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For this simulation of ship and tank motions in the seaways of interest, some approximations were made. First, it was assumed that $\sigma_{\dot{\tau}} \cong \omega_r \sigma_{\tau}$, which is very nearly true in the sea states of most interest. Second, a typical value of 7.0 degrees for the standard deviation of tank angle was used to compute a value for the equivalent linear damping ratio. This value, $\zeta_e = 0.274$, was then used for all computations regardless of the resulting standard deviation of tank angle or rate.

Other parameters also affect the performance of the tank. These are the moment of inertia of the free surface, which is 169,280 feet^4, and the quantity defined as s" in Reference 1, which ranges approximately from -44 feet (KG = 22 feet) to -38 feet (KG = 25 feet). The value of s" is large and negative because the stabilizer is located high on the ship. This factor contributes significantly to the effectiveness of the stabilizer.

LINEAR ANALYSIS OF STABILIZED SHIP PERFORMANCE

Introduction

In order to ascertain the expected roll stabilization of several of the stabilization systems, a computer-aided simulation of the behavior of the ship was performed for various random seaways and directions to the seaway for both zero speed and 12 knots forward way. In this section the computations based on the linearized model of the problem and the computer output are described. The results of this simulation are expected to be indicative of the ship and tank performance over a wide range of ocean environments in which the excitation is moderate. These results have proved to be representative of more sophisticated calculations which include such nonlinearities as quadratic tank damping, nonlinear roll damping, nonlinear restoring moment, and tank slamming (saturation), provided that the tank slamming occurs less often than every third cycle, and that the other nonlinear effects are properly modeled by equivalent linear terms.

Formulation of Linear Problem

The linearized simulation of the behavior was achieved with a digital computer program which is based on the formulation presented in Reference 1. In this model, the ship roll, sway, yaw, and the tank angle are derived from a set of five coupled linear differential equations. The system properties, i.e., the hydrodynamic forces and moments, are computed on the basis of a slender-ship theory, and the forcing functions due to the seaway allow for hydrostatic, velocity and acceleration effects. The equations of motion used in the linear analysis are obtained from Equations (24), (25), (26), and (27) of Reference 1 by retaining only the linear terms. The forcing functions are given by Equations (51), (52), (53), (54), (55) and (56) in the same reference.

Summary of Simulated Conditions

Computations based on linear theory were made for both zero speed and 12 knots forward way for each of the six loading conditions.

The behavior of the ship/tank system was computed for both regular (single frequency) and irregular (wave spectrum) waves. Irregular waves were modeled by the Pierson-Moscowitz spectrum corresponding to five sea states of significant wave heights of 8, 12, 20, 30 and 40 feet. The irregular seas were assumed to be both long-crested (unidirectional) and short-crested (multi-directional). In the case of the short-crested seas the directionality function used was a cosine-squared distribution.

Evaluation Criteria

The output of the simulation includes the ship motions and tank responses to regular waves (unit responses) and the statistical responses to both short-crested and long-crested seas. The following discussion is intended to provide guidance in the understanding and evaluation of these measures of the stabilizer performance.

The unit response of the ship at resonance is typically the most obvious single measure of performance. Stabilizer tanks are usually designed to minimize the ship roll response at resonance. For most ships underway in quartering seas, a stabilizer which minimizes roll response at resonance is very effective at reducing the rolling motions in the seaway, since under this condition many of the waves in the sea may be encountered at frequencies near roll resonance even though the waves are of higher frequencies.

The statistical roll motions of the ship are the most meaningful measure of performance. To arrive at the summary of results for long-crested and short-crested seas, the statistical responses of the system are calculated over a range of headings relative to the sea from head sea to following sea, that is 0° to 180°, at 15° intervals. The standard deviation (or rms, root mean square) of each response is computed. The largest value obtained over all headings is utilized in the summary of results. The results are presented in rms values because of the convenience in using them to determine the statistics of the motions. The following table provides typical conversions.

	half band-width (amplitude)	whole band-width (out-to-out motion)
Average		
all cycles	1.25 rms	2.50 rms
1/3 highest (significant)	2.00	4.00
1/10 highest	2.55	5.10
Value exceeded once per		
100 cycles	3.04	6.08
1000 cycles	3.72	7.44

The long-crested seaway statistics are obtained by multiplying the appropriate response amplitude operators (unit responses) by the relevant sea spectrum and integrating over the whole frequency domain. Thus, frequencies which cause large motions near resonance are included as well as those which do not cause severe motions. Since the tank reduces roll primarily at resonance, the roll reduction afforded by the stabilizer in a seaway, where many frequencies are present, is less than the roll reduction at resonance.

The short-crested seaway responses are formed by integrating the long-crested seaway responses over a range of track-to-wave angles, including headings which cause large motions and those which do not. As a result, the roll reductions attributed to the tank stabilizer are yet again less than those due to long-crested seas. Although discussion of the ship response in short-crested seas therefore leads to the smallest numerical values for roll reduction, these results are most meaningful since they represent most closely the values that one would measure in a real sea. The long-crested results are more appropriate to swell conditions.

The motions of the water in the stabilizer tank are important in the evaluation of the results. These motions are characterized by the "tank angle", the roll angle of the water in the tank relative to the ship. Saturation of the tank (slamming of the water in the tank against the top of the tank) occurs at a tank angle which depends on the geometry of the tank and the level of water in the tank. Examining the statistical (rms) tank angles in a seaway, one can expect incipient saturation to occur regularly (every seventh or eighth roll) when the rms tank angle is half the tank saturation angle. At this point the tank effectiveness is only slightly degraded by the saturation. One can expect significant saturation when the rms tank angle is 75 percent of the tank saturation angle. At this point and beyond, the effectiveness of the tank is severely degraded by the saturation phenomenon. The linearized theory does not include the effects of tank saturation, so the tank statistics must always be examined to assure that the computed roll reduction can reasonably be expected to be realized.

Results of Analysis

The results of the linear analysis are summarized in Tables 2, 3, and 4. Table 2 shows the maximum value of the roll response amplitude operator in regular waves from abeam. Table 3 displays the standard deviation (rms) of roll angle at the worst headings in short-crested seas. Table 4 presents the standard deviation of the angle of the water in the stabilizer at the worst headings in short-crested seas.

Comparison of these results with those presented in the preliminary design report, Reference 5, shows that the modified design represents an improvement over any of the stabilizers analyzed in the preliminary design study. The most significant factor is the reduction in damping achieved by reducing the amount of structure in the crossover duct.

It is interesting to note that the percent roll reductions at zero forward way vary dramatically with sea state, while the reductions at 12 knots forward way are relatively constant in the range of about 50 to 60%. The reductions at zero forward way are sensitive to the frequency content of the spectrum. The stabilizer reduces the roll response amplitude operator at roll resonance and nearby frequencies, but actually increases the roll response at high frequencies. Since the low sea states have most of the energy in the spectrum at high frequencies, the stabilizer is not effective at reducing roll in these seas at zero forward way. In contrast, with forward way, the largest roll response occurs not in a beam sea, but in a quartering sea where the ship over-taking the high-frequency waves causes the encounter frequency to match the ship roll resonant frequency. Note the substantial increase in maximum rms roll motion in Table 3 when the forward way is increased from zero to 12 knots in the low sea states. In these cases the stabilizer is effective, since the bulk of the roll excitation is near the resonant frequency.

A more complete listing of results is contained in Appendix A, in a separate volume. This appendix lists the principal characteristics of the ship and stabilizer for each loading condition, the unit responses in regular waves over a range of frequencies, and the statistical roll responses over the entire range of relative sea directions.

DESIGN DETAILS

Several details of the design are discussed in the following paragraphs. These and other details are shown on the final design drawing, Reference 8.

Water Level and Wing Height

The desired water level and the wing height depend on the statistics of the tank angle. Based on the values presented in Table 4, the largest standard deviation of tank angle to be expected in reasonably realistic seas is 11.2 degrees. This means that the standard deviation of water level in each wing can be expected to be about 4.5 feet. Considering that incipient saturation occurs when the st ndard deviation of tank angle is one-half the maximum angle of the tank, the nominal water level in the tank should be at least 9.0 feet. (When one wing runs dry, the tank is at its maximum angle.) We recommend a nominal water level of 9.5 feet.

The wing tanks must be high enough to preclude slamming of the water into the top of the tank. Therefore, the wing height should be twice the nominal water level plus a small margin. The total height available is 22.0 feet, 3.0 feet higher than twice the nominal water level. Thus the wing height is adequate without being excessively high.

Air Crossover Pipe

The air corssover pipe carries air from the top of one wing to the other. The pipe will penetrate the top of the wing tank, extending downward about 1.5 feet, in order to provide a cushion of air at the top of the wing tank in the event of extraordinarily violent motions of the water in the tank.

The diameter of the air crossover pipe is sized to avoid sonic flow in the pipe. The mean velocity in the pipe is limited to 500 feet per second for an extreme rate of motion of the water in the tank. The extreme rate is considered to be a sinusoidal motion 9.5 foot in amplitude at the tank resonant period of 10.8 seconds. The air displaced by the motion of the water must travel through the air crossover pipe. In order to carry this flow rate with velocity 500 feet per second or less, the air crossover pipe must be at least 1.50 feet in diameter.

Filling and Venting

The fill line may be installed as the ship designer prefers; we do not consider it part of the stabilizer design.

A vent or vents must be installed which is larger than the fill line in total cross section. We recommend a single vent in the crossover pipe as close as practicable to the ship centerline. The reason for this location is to minimize the breathing of the vent.

The stabilizer design includes an overflow system to preclude overfilling the tank. From the crossover duct, and at the ship centerline, an overflow pipe extends vertically. At a level 9.5 feet above the bottom of the duct, the pipe turns back down, eventually finding its way over the side of the ship in a conspicuous location. At that same point in the pipe 9.5 feet above the bottom of the duct another pipe joins the overflow pipe. This second pipe goes upward to a point above the top of the generator room, where it is vented to the atmosphere. With this arrangement the water in the stabilizer will visibly flow out the overflow pipe whenever the mean level of water in the stabilizer exceeds 9.5 feet.

Emergency Dumping System

Although it reduces the rolling motions of the ship, the stabilizer also reduces the static stability of the ship. In a dire emergency, it may be necessary to take all possible steps to maximize the static stability. For this reason it is desirable to have the capability to drain the stabilizer quickly.

The final design includes an emergency dumping capability. Four six-inch drain pipes, one from near each corner of the bottom of the tank, extend first downward about a foot, then turn to the horizontal, penetrate the outboard bulkhead of the compartment below the stabilizer, extend across the top of the exterior passageway, turn down again, extend down to just above the main deck, then turn outboard to discharge over the side. A remotely operated valve is to be installed in each pipe in the short run inside the compartment on the main deck below the stabilizer. The valves will be remotely operable from the bridge, but will also be manually operable.

If all four valves are opened, the tank will drain in approximately eight to ten minutes.

REFERENCES

1. Webster, W. C., "Analysis of the Control of Activated Antiroll Tanks", Transactions of the Society of Naval Architects and Marine Engineers, Volume 75, 1967, page 296.

2. "Preliminary Design Report for a Dual Draft Icebreaker", Naval Engineering Division, Electronics Engineering Division, U. S. Coast Guard, November 1, 1979.

3. "296-Foot WAGB Lines & Offsets", U. S. Coast Guard Naval Engineering drawing, provided by R. D. Fuller, Jr.

4. "Dual Draft Icebreaker Arrangements, Main Deck & 01 Level", U. S. Coast Guard Naval Engineering drawing dated 7/1/80, provided by R. D. Fuller, Jr.

5. "Preliminary Design of a Passive U-Tube Stabilizer for the United States Coast Guard Dual Draft Icebreaker", Ship Research Incorporated Report Number CG80-1, September 11, 1980.

6. "Bench Tests of a U-Tube Stabilizer for the Dual Draft Icebreaker", Ship Research Incorporated Report Number CG80-2, July 3, 1981.

7. "Comparative Model Tests of U-Tube and Free-Surface Roll Stabilizer Designs for the USCG Dual Draft Icebreaker", John F. Dalzell, Stevens Institute of Technology Davidson Laboratory Report SIT-DL-80-9-2166, November 1980.

8. Stabilizer Tank for the USCG Dual Draft Icebreaker, Ship Research Incorporated Drawing Number CG80-1, July 3, 1981.

	Eastern Arctic		Great Lakes			Model Test
	Full Load	50% Fuel	Full Load	50% Fuel	Burned Out	75% Fuel
Displacement, LT	7018	6177	6247	5768	5290	6646
Draft, ft.	24.30	23.10	22.80	21.80	20.10	23.66
KG, ft.	22.29	24.12	22.67	24.12	25.84	24.10
KB, ft.	13.68	13.00	12.90	12.30	11.40	13.33
GM, ft.	5.89	3.93	5.33	3.81	2.06	4.02
Roll Period, sec.	10.68	13.07	11.23	13.28	18.06	12.80
Stabilizer % GM loss	11.7	19.9	14.2	21.5	43.3	18.1

Table 1. SUMMARY OF SHIP LOADING CONDITIONS

Loading Condition	Speed knots	Un-Stabilized	Stabilized	% Reduction
Eastern Arctic	0	7.40	1.40	81
Full Load	12	4.19	1.30	69
Eastern Arctic	0	5.15	0.58	89
50% Fuel	12	2.64	0.57	78
Great Lakes	0	6.88	1.10	84
Full Load	12	3.76	1.05	72
Great Lakes	0	5.07	0.55	89
50% Fuel	12	2.53	0.56	78
Great Lakes	0	2.84	0.29	90
Burned Out	12	1.16	0.31	73
Model Test	0	5.29	0.61	89
75% Fuel	12	2.75	0.61	78

Note: Values are amplitude of roll angle per amplitude (one-half height) of wave, degrees/foot

Table 2. SUMMARY OF MAXIMUM VALUES OF ROLL RESPONSE AMPLITUDE OPERATOR IN BEAM SEA REGULAR WAVES

Loading Condition	H_{sig} ft.	Speed = 0 Stabilizer No	yes	Percent Reduc.	Speed = 12 knots Stabilizer No	Yes	Percent Reduc.
Eastern	8	1.9	1.2	39	4.2	2.2	47
Arctic	12	5.5	2.3	58	6.3	3.3	48
Full Load	20	10.2	3.9	62	8.8	4.7	47
	30	12.5	5.1	60	10.3	5.6	46
	40	13.5	5.8	58	11.0	6.2	44
Eastern	8	0.4	0.5	-29	5.9	2.3	60
Arctic	12	1.8	1.0	43	8.6	3.5	60
50% Fuel	20	5.9	2.0	67	11.4	5.0	57
	30	9.1	3.0	67	13.3	6.1	54
	40	10.8	3.9	64	14.1	6.7	52
Great	8	1.3	0.9	24	5.5	2.3	59
Lakes	12	4.6	1.9	59	7.6	3.3	56
Full Load	20	9.9	3.3	67	10.1	4.7	54
	30	12.9	4.5	65	11.5	5.7	50
	40	14.2	5.2	63	12.2	6.3	48
Great	8	0.4	0.5	-39	6.6	2.3	65
Lakes	12	1.5	1.0	34	9.6	3.4	65
50% Fuel	20	5.3	1.9	65	12.5	4.9	61
	30	8.5	2.8	67	14.2	6.0	58
	40	10.3	3.7	64	15.1	6.7	56
Great	8	0.2	0.3	-56	4.0	1.8	56
Lakes	12	0.3	0.5	-83	6.0	2.3	61
Burned Out	20	1.5	0.9	38	10.1	3.1	69
	30	6.1	1.2	80	14.0	3.8	73
	40	10.5	1.5	86	16.2	4.5	72
Model	8	0.4	0.5	-18	5.3	2.3	56
Test	12	2.4	1.1	55	7.8	3.4	56
75% Fuel	20	7.6	2.1	73	10.8	4.9	55
	30	11.3	3.3	71	12.6	5.9	53
	40	13.1	4.1	69	13.5	6.6	52

Table 3. SUMMARY OF COMPUTED RMS ROLL ANGLES AT WORST HEADINGS IN SHORT-CRESTED SEAS. SHIP WITH AND WITHOUT STABILIZER.

Loading Condition	H_{sig} ft.	Speed = 0	Speed = 12 knots
Eastern Arctic Full Load	8	2.4	4.1
	12	4.8	6.1
	20	7.7	8.3
	30	9.4	9.6
	40	10.2	10.2
Eastern Arctic 50% Fuel	8	1.5	4.4
	12	3.0	6.4
	20	5.1	8.8
	30	6.9	10.4
	40	8.0	11.2
Great Lakes Full Load	8	2.1	4.3
	12	4.2	6.3
	20	6.9	8.4
	30	8.6	9.8
	40	9.5	10.4
Great Lakes 50% Fuel	8	1.5	4.4
	12	2.9	6.4
	20	5.0	8.7
	30	6.6	10.2
	40	7.6	11.2
Great Lakes Burned Out	8	1.1	3.4
	12	2.0	4.7
	20	3.3	6.3
	30	4.2	7.5
	40	4.8	8.4
Model Test 75% Fuel	8	1.6	4.4
	12	3.1	6.4
	20	5.4	8.7
	30	7.2	10.2
	40	8.2	11.0

Table 4. SUMMARY OF MAXIMUM RMS TANK ANGLES IN SHORT-CRESTED SEAS.

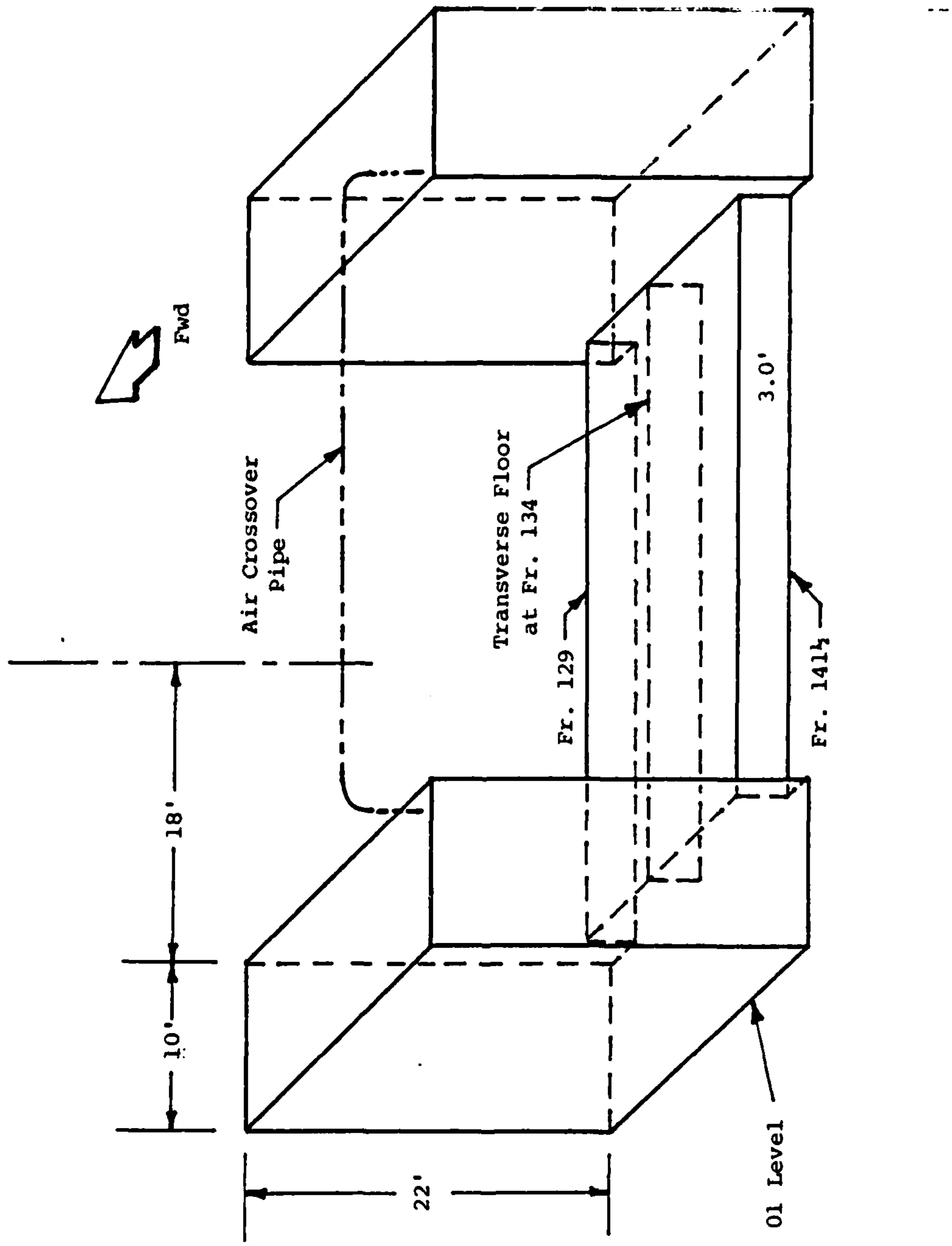

Figure 1. Schematic of Stabilizer Configuration

DESIGN AND ANALYSIS OF
A PASSIVE STABILIZER FOR
THE COAST GUARD
DUAL DRAFT ICEBREAKER

Appendix A

Report Number CG80-3

July 3, 1981

Prepared for

Davidson Laboratory
Stevens Institute of Technology
Hoboken, New Jersey

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Definitions

The following pages are computer listings of the performance calculations of the stabilized and unstabilized ship. The listings are in three formats, described below.

The first format is the listing of the system parameters, that is, the major characteristics of the ship and the stabilizer tank(s). The listing is self-explanatory. The damping ratio displayed applies only to the zero speed condition.

The second format is the unit responses, that is, the response of the ship and stabilizer tank(s) to regular waves. PERIOD is the wave period in seconds. FREQ is the wave frequency in radians per second. OMEGA is the ratio of the wave frequency to the ship roll resonant frequency. ROLL is the unit response in roll, the amplitude of roll in degrees divided by the wave amplitude (half-height) in feet. TANK1 and TANK2 are the unit responses of the stabilizers #1 and #2, if present, the amplitude of tank angle in degrees divided by the wave amplitude in feet.

The final format is a table of statistical responses in a seaway. DIRECTION is the direction of the sea relative to the ship, 0° being a stern sea. The table shows the standard deviation of roll in degrees as a function of significant wave height and sea direction for both long-crested and short-crested seas.

SYSTEM PARAMETERS
DUAL DRAFT ICEBREAKER
STABILIZED
EASTERN ARCTIC - FULL LOAD

SHIP PARAMETERS

LENGTH	276.00 FT	BG	8.61 FT	GM	5.89 FT
BEAM	64.80 FT				
DRAFT	24.30 FT	ROLL PERIOD		10.68	SECONDS
DISPLMT	7018 LT	DAMPING RATIO		.025	

TANK PARAMETERS

	PERIOD SEC.	PERCENT GM LOSS	DAMPING RATIO	SPP	FEET FWD CG
TANK1	10.80	11.42	.274	-44.40	4.00
TANK2	0.	0.	0.	0.	0.

SYSTEM PARAMETERS
DUAL DRAFT ICEBREAKER
STABILIZED
EASTERN ARCTIC - 50 PCT. FUEL

SHIP PARAMETERS

LENGTH	276.00 FT	BG	11.12 FT	GM	3.93 FT
BEAM	64.80 FT				
DRAFT	23.10 FT	ROLL PERIOD		13.07	SECONDS
DISPLMT	6177 LT	DAMPING RATIO		.025	

TANK PARAMETERS

	PERIOD SEC.	PERCENT GM LOSS	DAMPING RATIO	SPP	FEET FWD CG
TANK1	10.80	19.43	.274	-40.80	4.00
TANK2	0.	0.	0.	0.	0.

SYSTEM PARAMETERS
DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - FULL LOAD

SHIP PARAMETERS

LENGTH	276.00 FT	BG	9.77 FT	GM	5.33 FT
BEAM	64.80 FT				
DRAFT	22.80 FT	ROLL PERIOD		11.23	SECONDS
DISPLMT	6247 LT	DAMPING RATIO		.025	

TANK PARAMETERS

	PERIOD SEC.	PERCENT GM LOSS	DAMPING RATIO	SPP	FEET FWD CG
TANK1	10.80	14.17	.274	-43.70	4.00
TANK2	0.	0.	0.	0.	0.

SYSTEM PARAMETERS
DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - 50 PCT. FUEL

SHIP PARAMETERS

LENGTH	276.00 FT	BG	11.82 FT	GM	3.81 FT
BEAM	64.80 FT				
DRAFT	21.80 FT	ROLL PERIOD		13.28 SECONDS	
DISPLMT	5768 LT	DAMPING RATIO		.025	

TANK PARAMETERS

	PERIOD SEC.	PERCENT GM LOSS	DAMPING RATIO	SPP	FEET FWD CG
TANK1	10.80	21.46	.274	-40.80	4.00
TANK2	0.	0.	0.	0.	0.

SYSTEM PARAMETERS
DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - BURNED OUT

SHIP PARAMETERS

LENGTH	276.00 FT	BG	14.44 FT	GM	2.06 FT
BEAM	64.80 FT				
DRAFT	20.10 FT	ROLL PERIOD		18.06	SECONDS
DISPLMT	5290 LT	DAMPING RATIO		.025	

TANK PARAMETERS

	PERIOD SEC.	PERCENT GM LOSS	DAMPING RATIO	SPP	FEET FWD CG
TANK1	10.80	43.30	.274	-37.30	4.00
TANK2	0.	0.	0.	0.	0.

SYSTEM PARAMETERS
DUAL DRAFT ICEBREAKER
STABILIZED
MODEL TEST CONDITION

SHIP PARAMETERS

LENGTH	276.00 FT	BG 10.77 FT	GM 4.02 FT
BEAM	64.80 FT		
DRAFT	23.66 FT	ROLL PERIOD	12.80 SECONDS
DISPLMT	6647 LT	DAMPING RATIO	.025

TANK PARAMETERS

	PERIOD SEC.	PERCENT GM LOSS	DAMPING RATIO	SPP	FEET FWD CG
TANK1	10.80	18.10	.274	-40.80	4.00
TANK2	0.	0.	0.	0.	0.

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
NO STABILIZER
EASTERN ARCTIC - FULL LOAD
SPEED = 0. KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
53.40	.1177	.20	.025	.000	.000
35.60	.1765	.30	.058	.000	.000
26.70	.2353	.40	.109	.000	.000
21.36	.2942	.50	.182	.000	.000
17.80	.3530	.60	.291	.000	.000
15.26	.4118	.70	.465	.000	.000
13.35	.4706	.80	.793	.000	.000
12.56	.5001	.85	1.106	.000	.000
11.87	.5295	.90	1.701	.000	.000
11.24	.5589	.95	3.245	.000	.000
10.90	.5765	.98	5.757	.000	.000
10.68	.5883	1.00	7.405	.000	.000
10.47	.6001	1.02	5.802	.000	.000
10.17	.6177	1.05	3.354	.000	.000
9.71	.6471	1.10	1.837	.000	.000
9.29	.6765	1.15	1.247	.000	.000
8.90	.7060	1.20	.935	.000	.000
8.22	.7648	1.30	.604	.000	.000
7.63	.8236	1.40	.425	.000	.000
6.68	.9413	1.60	.228	.000	.000
5.93	1.0589	1.80	.122	.000	.000
5.09	1.2354	2.10	.047	.000	.000
4.27	1.4707	2.50	.024	.000	.000
3.56	1.7649	3.00	.049	.000	.000
2.67	2.3532	4.00	.015	.000	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
NO STABILIZER
EASTERN ARCTIC - 50 PCT. FUEL
SPEED = 0. KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
65.37	.0961	.20	.017	.000	.000
43.58	.1442	.30	.039	.000	.000
32.68	.1922	.40	.073	.000	.000
26.15	.2403	.50	.123	.000	.000
21.79	.2884	.60	.197	.000	.000
18.68	.3364	.70	.317	.000	.000
16.34	.3845	.80	.544	.000	.000
15.38	.4085	.85	.762	.000	.000
14.53	.4325	.90	1.175	.000	.000
13.76	.4566	.95	2.248	.000	.000
13.34	.4710	.98	3.994	.000	.000
13.07	.4806	1.00	5.151	.000	.000
12.82	.4902	1.02	4.047	.000	.000
12.45	.5046	1.05	2.343	.000	.000
11.89	.5287	1.10	1.286	.000	.000
11.37	.5527	1.15	.875	.000	.000
10.89	.5767	1.20	.657	.000	.000
10.06	.6248	1.30	.425	.000	.000
9.34	.6728	1.40	.297	.000	.000
8.17	.7690	1.60	.152	.000	.000
7.26	.8651	1.80	.069	.000	.000
6.23	1.0093	2.10	.040	.000	.000
5.23	1.2015	2.50	.064	.000	.000
4.36	1.4418	3.00	.031	.000	.000
3.27	1.9224	4.00	.073	.000	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
NO STABILIZER
GREAT LAKES - FULL LOAD
SPEED = 0. KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
56.14	.1119	.20	.023	.000	.000
37.43	.1679	.30	.053	.000	.000
28.07	.2238	.40	.099	.000	.000
22.46	.2798	.50	.166	.000	.000
18.71	.3358	.60	.266	.000	.000
16.04	.3917	.70	.426	.000	.000
14.03	.4477	.80	.730	.000	.000
13.21	.4757	.85	1.020	.000	.000
12.48	.5036	.90	1.572	.000	.000
11.82	.5316	.95	3.006	.000	.000
11.46	.5484	.98	5.340	.000	.000
11.23	.5596	1.00	6.880	.000	.000
11.01	.5708	1.02	5.400	.000	.000
10.69	.5876	1.05	3.127	.000	.000
10.21	.6156	1.10	1.717	.000	.000
9.76	.6435	1.15	1.168	.000	.000
9.36	.6715	1.20	.878	.000	.000
8.64	.7275	1.30	.571	.000	.000
8.02	.7834	1.40	.405	.000	.000
7.02	.8954	1.60	.219	.000	.000
6.24	1.0073	1.80	.117	.000	.000
5.35	1.1752	2.10	.044	.000	.000
4.49	1.3990	2.50	.022	.000	.000
3.74	1.6788	3.00	.046	.000	.000
2.81	2.2384	4.00	.039	.000	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
NO STABILIZER
GREAT LAKES - 50 PCT. FUEL
SPEED = 0. KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
66.39	.0946	.20	.016	.000	.000
44.26	.1420	.30	.038	.000	.000
33.20	.1893	.40	.071	.000	.000
26.56	.2366	.50	.120	.000	.000
22.13	.2839	.60	.192	.000	.000
18.97	.3312	.70	.309	.000	.000
16.60	.3786	.80	.533	.000	.000
15.62	.4022	.85	.746	.000	.000
14.75	.4259	.90	1.153	.000	.000
13.98	.4495	.95	2.208	.000	.000
13.55	.4637	.98	3.927	.000	.000
13.28	.4732	1.00	5.070	.000	.000
13.02	.4827	1.02	3.987	.000	.000
12.65	.4969	1.05	2.311	.000	.000
12.07	.5205	1.10	1.271	.000	.000
11.55	.5442	1.15	.866	.000	.000
11.07	.5678	1.20	.652	.000	.000
10.21	.6152	1.30	.424	.000	.000
9.48	.6625	1.40	.299	.000	.000
8.30	.7571	1.60	.155	.000	.000
7.38	.8518	1.80	.073	.000	.000
6.32	.9937	2.10	.038	.000	.000
5.31	1.1830	2.50	.064	.000	.000
4.43	1.4196	3.00	.034	.000	.000
3.32	1.8928	4.00	.082	.000	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
NO STABILIZER
GREAT LAKES - BURNED OUT
SPEED = 0. KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
90.30	.0696	.20	.009	.000	.000
60.20	.1044	.30	.021	.000	.000
45.15	.1392	.40	.039	.000	.000
36.12	.1739	.50	.065	.000	.000
30.10	.2087	.60	.105	.000	.000
25.80	.2435	.70	.171	.000	.000
22.58	.2783	.80	.295	.000	.000
21.25	.2957	.85	.415	.000	.000
20.07	.3131	.90	.642	.000	.000
19.01	.3305	.95	1.232	.000	.000
18.43	.3409	.98	2.194	.000	.000
18.06	.3479	1.00	2.841	.000	.000
17.71	.3549	1.02	2.241	.000	.000
17.20	.3653	1.05	1.300	.000	.000
16.42	.3827	1.10	.716	.000	.000
15.70	.4001	1.15	.488	.000	.000
15.05	.4175	1.20	.368	.000	.000
13.89	.4523	1.30	.238	.000	.000
12.90	.4871	1.40	.166	.000	.000
11.29	.5566	1.60	.081	.000	.000
10.03	.6262	1.80	.031	.000	.000
8.60	.7306	2.10	.053	.000	.000
7.22	.8697	2.50	.111	.000	.000
6.02	1.0437	3.00	.146	.000	.000
4.52	1.3916	4.00	.079	.000	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
NO STABILIZER
MODEL TEST CONDITION
SPEED = 0. KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
64.00	.0982	.20	.018	.000	.000
42.66	.1473	.30	.041	.000	.000
32.00	.1964	.40	.076	.000	.000
25.60	.2454	.50	.128	.000	.000
21.33	.2945	.60	.205	.000	.000
18.28	.3436	.70	.328	.000	.000
16.00	.3927	.80	.562	.000	.000
15.06	.4173	.85	.786	.000	.000
14.22	.4418	.90	1.210	.000	.000
13.47	.4664	.95	2.311	.000	.000
13.06	.4811	.98	4.102	.000	.000
12.80	.4909	1.00	5.285	.000	.000
12.55	.5007	1.02	4.148	.000	.000
12.19	.5154	1.05	2.399	.000	.000
11.64	.5400	1.10	1.314	.000	.000
11.13	.5645	1.15	.891	.000	.000
10.67	.5891	1.20	.667	.000	.000
9.85	.6382	1.30	.429	.000	.000
9.14	.6873	1.40	.298	.000	.000
8.00	.7854	1.60	.149	.000	.000
7.11	.8836	1.80	.066	.000	.000
6.09	1.0309	2.10	.042	.000	.000
5.12	1.2272	2.50	.063	.000	.000
4.27	1.4727	3.00	.025	.000	.000
3.20	1.9636	4.00	.071	.000	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
STABILIZED
EASTERN ARCTIC - FULL LOAD
SPEED = 0. KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
53.40	.1177	.20	.025	.001	.000
35.60	.1765	.30	.059	.006	.000
26.70	.2353	.40	.112	.022	.000
21.36	.2942	.50	.192	.069	.000
17.80	.3530	.60	.319	.194	.000
15.26	.4118	.70	.528	.518	.000
13.35	.4706	.80	.772	1.127	.000
12.56	.5001	.85	.844	1.425	.000
11.87	.5295	.90	.896	1.677	.000
11.24	.5589	.95	.966	1.924	.000
10.90	.5765	.98	1.026	2.090	.000
10.68	.5883	1.00	1.074	2.210	.000
10.47	.6001	1.02	1.128	2.338	.000
10.17	.6177	1.05	1.215	2.540	.000
9.71	.6471	1.10	1.351	2.843	.000
9.29	.6765	1.15	1.398	2.958	.000
8.90	.7060	1.20	1.306	2.782	.000
8.22	.7648	1.30	.938	2.051	.000
7.63	.8236	1.40	.646	1.481	.000
6.68	.9413	1.60	.333	.893	.000
5.93	1.0589	1.80	.180	.607	.000
5.09	1.2354	2.10	.073	.364	.000
4.27	1.4707	2.50	.033	.165	.000
3.56	1.7649	3.00	.050	.021	.000
2.67	2.3532	4.00	.015	.012	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
STABILIZED
EASTERN ARCTIC - 50 PCT. FUEL
SPEED = 0. KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
65.37	.0961	.20	.017	.001	.000
43.58	.1442	.30	.040	.004	.000
32.68	.1922	.40	.076	.015	.000
26.15	.2403	.50	.134	.045	.000
21.79	.2884	.60	.231	.128	.000
18.68	.3364	.70	.406	.360	.000
16.34	.3845	.80	.578	.790	.000
15.38	.4085	.85	.551	.912	.000
14.53	.4325	.90	.490	.956	.000
13.76	.4566	.95	.444	.988	.000
13.34	.4710	.98	.428	1.014	.000
13.07	.4806	1.00	.422	1.035	.000
12.82	.4902	1.02	.420	1.059	.000
12.45	.5046	1.05	.423	1.103	.000
11.89	.5287	1.10	.440	1.195	.000
11.37	.5527	1.15	.470	1.306	.000
10.89	.5767	1.20	.506	1.430	.000
10.06	.6248	1.30	.566	1.647	.000
9.34	.6728	1.40	.550	1.671	.000
8.17	.7690	1.60	.349	1.245	.000
7.26	.8651	1.80	.189	.882	.000
6.23	1.0093	2.10	.070	.583	.000
5.23	1.2015	2.50	.049	.362	.000
4.36	1.4418	3.00	.025	.180	.000
3.27	1.9224	4.00	.072	.016	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - FULL LOAD
SPEED = 0. KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
56.14	.1119	.20	.023	.001	.000
37.43	.1679	.30	.054	.006	.000
28.07	.2238	.40	.102	.021	.000
22.46	.2798	.50	.177	.063	.000
18.71	.3358	.60	.299	.179	.000
16.04	.3917	.70	.501	.485	.000
14.03	.4477	.80	.706	1.029	.000
13.21	.4757	.85	.733	1.249	.000
12.48	.5036	.90	.736	1.409	.000
11.82	.5316	.95	.754	1.558	.000
11.46	.5484	.98	.779	1.659	.000
11.23	.5596	1.00	.803	1.733	.000
11.01	.5708	1.02	.831	1.815	.000
10.69	.5876	1.05	.882	1.948	.000
10.21	.6156	1.10	.980	2.189	.000
9.76	.6435	1.15	1.068	2.400	.000
9.36	.6715	1.20	1.100	2.489	.000
8.64	.7275	1.30	.936	2.172	.000
8.02	.7834	1.40	.683	1.657	.000
7.02	.8954	1.60	.359	1.014	.000
6.24	1.0073	1.80	.196	.698	.000
5.35	1.1752	2.10	.080	.438	.000
4.49	1.3990	2.50	.034	.227	.000
3.74	1.6788	3.00	.049	.059	.000
2.81	2.2384	4.00	.038	.025	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - 50 PCT. FUEL
SPEED = 0. KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
66.39	.0946	.20	.016	.001	.000
44.26	.1420	.30	.039	.004	.000
33.20	.1893	.40	.075	.015	.000
26.56	.2366	.50	.132	.045	.000
22.13	.2839	.60	.230	.131	.000
18.97	.3312	.70	.404	.369	.000
16.60	.3786	.80	.533	.746	.000
15.62	.4022	.85	.490	.828	.000
14.75	.4259	.90	.433	.859	.000
13.98	.4495	.95	.394	.888	.000
13.55	.4637	.98	.382	.912	.000
13.28	.4732	1.00	.379	.933	.000
13.02	.4827	1.02	.378	.956	.000
12.65	.4969	1.05	.382	.997	.000
12.07	.5205	1.10	.400	1.083	.000
11.55	.5442	1.15	.430	1.188	.000
11.07	.5678	1.20	.467	1.308	.000
10.21	.6152	1.30	.540	1.549	.000
9.48	.6625	1.40	.554	1.652	.000
8.30	.7571	1.60	.380	1.312	.000
7.38	.8518	1.80	.212	.938	.000
6.32	.9937	2.10	.081	.623	.000
5.31	1.1830	2.50	.048	.394	.000
4.43	1.4196	3.00	.026	.207	.000
3.32	1.8928	4.00	.082	.009	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - BURNED OUT
SPEED = 0. KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
90.30	.0696	.20	.009	.000	.000
60.20	.1044	.30	.022	.003	.000
45.15	.1392	.40	.044	.011	.000
36.12	.1739	.50	.084	.037	.000
30.10	.2087	.60	.161	.115	.000
25.80	.2435	.70	.210	.239	.000
22.58	.2783	.80	.149	.255	.000
21.25	.2957	.85	.125	.257	.000
20.07	.3131	.90	.111	.263	.000
19.01	.3305	.95	.104	.275	.000
18.43	.3409	.98	.103	.283	.000
18.06	.3479	1.00	.102	.290	.000
17.71	.3549	1.02	.103	.298	.000
17.20	.3653	1.05	.105	.310	.000
16.42	.3827	1.10	.111	.333	.000
15.70	.4001	1.15	.120	.361	.000
15.05	.4175	1.20	.130	.393	.000
13.89	.4523	1.30	.157	.470	.000
12.90	.4871	1.40	.188	.568	.000
11.29	.5566	1.60	.254	.826	.000
10.03	.6262	1.80	.287	1.073	.000
8.60	.7306	2.10	.193	1.022	.000
7.22	.8697	2.50	.092	.719	.000
6.02	1.0437	3.00	.110	.493	.000
4.52	1.3916	4.00	.065	.229	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
STABILIZED
MODEL TEST CONDITION
SPEED = 0. KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
64.00	.0982	.20	.018	.001	.000
42.66	.1473	.30	.042	.004	.000
32.00	.1964	.40	.079	.015	.000
25.60	.2454	.50	.138	.046	.000
21.33	.2945	.60	.236	.130	.000
18.28	.3436	.70	.412	.362	.000
16.00	.3927	.80	.604	.819	.000
15.06	.4173	.85	.591	.970	.000
14.22	.4418	.90	.534	1.032	.000
13.47	.4664	.95	.488	1.073	.000
13.06	.4811	.98	.472	1.103	.000
12.80	.4909	1.00	.467	1.127	.000
12.55	.5007	1.02	.465	1.155	.000
12.19	.5154	1.05	.469	1.205	.000
11.64	.5400	1.10	.490	1.306	.000
11.13	.5645	1.15	.523	1.428	.000
10.67	.5891	1.20	.561	1.557	.000
9.85	.6382	1.30	.607	1.740	.000
9.14	.6873	1.40	.556	1.674	.000
8.00	.7854	1.60	.329	1.179	.000
7.11	.8836	1.80	.172	.828	.000
6.09	1.0309	2.10	.063	.543	.000
5.12	1.2272	2.50	.049	.330	.000
4.27	1.4727	3.00	.020	.155	.000
3.20	1.9636	4.00	.070	.021	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
NO STABILIZER
EASTERN ARCTIC - FULL LOAD
SPEED = 12.0 KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
53.40	.1177	.20	.025	.000	.000
35.60	.1765	.30	.058	.000	.000
26.70	.2353	.40	.109	.000	.000
21.36	.2942	.50	.182	.000	.000
17.80	.3530	.60	.290	.000	.000
15.26	.4118	.70	.463	.000	.000
13.35	.4706	.80	.784	.000	.000
12.56	.5001	.85	1.082	.000	.000
11.87	.5295	.90	1.616	.000	.000
11.24	.5589	.95	2.739	.000	.000
10.90	.5765	.98	3.814	.000	.000
10.68	.5883	1.00	4.195	.000	.000
10.47	.6001	1.02	3.832	.000	.000
10.17	.6177	1.05	2.812	.000	.000
9.71	.6471	1.10	1.739	.000	.000
9.29	.6765	1.15	1.221	.000	.000
8.90	.7060	1.20	.929	.000	.000
8.22	.7648	1.30	.609	.000	.000
7.63	.8236	1.40	.434	.000	.000
6.68	.9413	1.60	.240	.000	.000
5.93	1.0589	1.80	.138	.000	.000
5.09	1.2354	2.10	.067	.000	.000
4.27	1.4707	2.50	.034	.000	.000
3.56	1.7649	3.00	.049	.000	.000
2.67	2.3532	4.00	.016	.000	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
NO STABILIZER
EASTERN ARCTIC - 50 PCT. FUEL
SPEED = 12.0 KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
65.37	.0961	.20	.017	.000	.000
43.58	.1442	.30	.039	.000	.000
32.68	.1922	.40	.073	.000	.000
26.15	.2403	.50	.123	.000	.000
21.79	.2884	.60	.197	.000	.000
18.68	.3364	.70	.316	.000	.000
16.34	.3845	.80	.536	.000	.000
15.38	.4085	.85	.740	.000	.000
14.53	.4325	.90	1.098	.000	.000
13.76	.4566	.95	1.811	.000	.000
13.34	.4710	.98	2.428	.000	.000
13.07	.4806	1.00	2.636	.000	.000
12.82	.4902	1.02	2.454	.000	.000
12.45	.5046	1.05	1.878	.000	.000
11.89	.5287	1.10	1.199	.000	.000
11.37	.5527	1.15	.853	.000	.000
10.89	.5767	1.20	.653	.000	.000
10.06	.6248	1.30	.431	.000	.000
9.34	.6728	1.40	.307	.000	.000
8.17	.7690	1.60	.168	.000	.000
7.26	.8651	1.80	.095	.000	.000
6.23	1.0093	2.10	.069	.000	.000
5.23	1.2015	2.50	.077	.000	.000
4.36	1.4418	3.00	.040	.000	.000
3.27	1.9224	4.00	.073	.000	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
NO STABILIZER
GREAT LAKES - FULL LOAD
SPEED = 12.0 KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
56.14	.1119	.20	.023	.000	.000
37.43	.1679	.30	.053	.000	.000
28.07	.2238	.40	.099	.000	.000
22.46	.2798	.50	.166	.000	.000
18.71	.3358	.60	.265	.000	.000
16.04	.3917	.70	.424	.000	.000
14.03	.4477	.80	.721	.000	.000
13.21	.4757	.85	.996	.000	.000
12.48	.5036	.90	1.486	.000	.000
11.82	.5316	.95	2.498	.000	.000
11.46	.5484	.98	3.436	.000	.000
11.23	.5596	1.00	3.764	.000	.000
11.01	.5708	1.02	3.464	.000	.000
10.69	.5876	1.05	2.582	.000	.000
10.21	.6156	1.10	1.617	.000	.000
9.76	.6435	1.15	1.142	.000	.000
9.36	.6715	1.20	.873	.000	.000
8.64	.7275	1.30	.577	.000	.000
8.02	.7834	1.40	.414	.000	.000
7.02	.8954	1.60	.233	.000	.000
6.24	1.0073	1.80	.135	.000	.000
5.35	1.1752	2.10	.069	.000	.000
4.49	1.3990	2.50	.039	.000	.000
3.74	1.6788	3.00	.047	.000	.000
2.81	2.2384	4.00	.039	.000	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
NO STABILIZER
GREAT LAKES - 50 PCT. FUEL
SPEED = 12.0 KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
66.39	.0946	.20	.016	.000	.000
44.26	.1420	.30	.038	.000	.000
33.20	.1893	.40	.071	.000	.000
26.56	.2366	.50	.119	.000	.000
22.13	.2839	.60	.192	.000	.000
18.97	.3312	.70	.308	.000	.000
16.60	.3786	.80	.524	.000	.000
15.62	.4022	.85	.723	.000	.000
14.75	.4259	.90	1.072	.000	.000
13.98	.4495	.95	1.756	.000	.000
13.55	.4637	.98	2.334	.000	.000
13.28	.4732	1.00	2.527	.000	.000
13.02	.4827	1.02	2.364	.000	.000
12.65	.4969	1.05	1.828	.000	.000
12.07	.5205	1.10	1.180	.000	.000
11.55	.5442	1.15	.843	.000	.000
11.07	.5678	1.20	.647	.000	.000
10.21	.6152	1.30	.430	.000	.000
9.48	.6625	1.40	.309	.000	.000
8.30	.7571	1.60	.171	.000	.000
7.38	.8518	1.80	.099	.000	.000
6.32	.9937	2.10	.070	.000	.000
5.31	1.1830	2.50	.079	.000	.000
4.43	1.4196	3.00	.044	.000	.000
3.32	1.8928	4.00	.083	.000	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
NO STABILIZER
GREAT LAKES - BURNED OUT
SPEED = 12.0 KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
90.30	.0696	.20	.009	.000	.000
60.20	.1044	.30	.021	.000	.000
45.15	.1392	.40	.039	.000	.000
36.12	.1739	.50	.065	.000	.000
30.10	.2087	.60	.105	.000	.000
25.80	.2435	.70	.169	.000	.000
22.58	.2783	.80	.288	.000	.000
21.25	.2957	.85	.394	.000	.000
20.07	.3131	.90	.572	.000	.000
19.01	.3305	.95	.880	.000	.000
18.43	.3409	.98	1.095	.000	.000
18.06	.3479	1.00	1.161	.000	.000
17.71	.3549	1.02	1.115	.000	.000
17.20	.3653	1.05	.924	.000	.000
16.42	.3827	1.10	.638	.000	.000
15.70	.4001	1.15	.469	.000	.000
15.05	.4175	1.20	.365	.000	.000
13.89	.4523	1.30	.246	.000	.000
12.90	.4871	1.40	.177	.000	.000
11.29	.5566	1.60	.099	.000	.000
10.03	.6262	1.80	.063	.000	.000
8.60	.7306	2.10	.075	.000	.000
7.22	.8697	2.50	.122	.000	.000
6.02	1.0437	3.00	.153	.000	.000
4.52	1.3916	4.00	.084	.000	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
NO STABILIZER
MODEL TEST CONDITION
SPEED = 12.0 KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
64.00	.0982	.20	.018	.000	.000
42.66	.1473	.30	.041	.000	.000
32.00	.1964	.40	.076	.000	.000
25.60	.2454	.50	.128	.000	.000
21.33	.2945	.60	.204	.000	.000
18.28	.3436	.70	.327	.000	.000
16.00	.3927	.80	.554	.000	.000
15.06	.4173	.85	.764	.000	.000
14.22	.4418	.90	1.134	.000	.000
13.47	.4664	.95	1.876	.000	.000
13.06	.4811	.98	[illegible].528	.000	.000
12.80	.4909	1.00	2.747	.000	.000
12.55	.5007	1.02	2.550	.000	.000
12.19	.5154	1.05	1.937	.000	.000
11.64	.5400	1.10	1.229	.000	.000
11.13	.5645	1.15	.870	.000	.000
10.67	.5891	1.20	.664	.000	.000
9.85	.6382	1.30	.435	.000	.000
9.14	.6873	1.40	.308	.000	.000
8.00	.7854	1.60	.165	.000	.000
7.11	.8836	1.80	.092	.000	.000
6.09	1.0309	2.10	.069	.000	.000
5.12	1.2272	2.50	.075	.000	.000
4.27	1.4727	3.00	.033	.000	.000
3.20	1.9636	4.00	.071	.000	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
STABILIZED
EASTERN ARCTIC - FULL LOAD
SPEED = 12.0 KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
53.40	.1177	.20	.025	.001	.000
35.60	.1765	.30	.059	.006	.000
26.70	.2353	.40	.112	.022	.000
21.36	.2942	.50	.191	.068	.000
17.80	.3530	.60	.317	.191	.000
15.26	.4118	.70	.513	.497	.000
13.35	.4706	.80	.724	1.036	.000
12.56	.5001	.85	.786	1.297	.000
11.87	.5295	.90	.836	1.525	.000
11.24	.5589	.95	.903	1.751	.000
10.90	.5765	.98	.958	1.900	.000
10.68	.5883	1.00	1.001	2.007	.000
10.47	.6001	1.02	1.049	2.120	.000
10.17	.6177	1.05	1.126	2.295	.000
9.71	.6471	1.10	1.247	2.561	.000
9.29	.6765	1.15	1.301	2.687	.000
8.90	.7060	1.20	1.240	2.580	.000
8.22	.7648	1.30	.929	1.981	.000
7.63	.8236	1.40	.655	1.458	.000
6.68	.9413	1.60	.347	.888	.000
5.93	1.0589	1.80	.196	.606	.000
5.09	1.2354	2.10	.090	.363	.000
4.27	1.4707	2.50	.042	.165	.000
3.56	1.7649	3.00	.050	.021	.000
2.67	2.3532	4.00	.015	.012	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
STABILIZED
EASTERN ARCTIC - 50 PCT. FUEL
SPEED = 12.0 KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
65.37	.0961	.20	.017	.001	.000
43.58	.1442	.30	.040	.004	.000
32.68	.1922	.40	.076	.015	.000
26.15	.2403	.50	.133	.044	.000
21.79	.2884	.60	.227	.124	.000
18.68	.3364	.70	.381	.331	.000
16.34	.3845	.80	.511	.674	.000
15.38	.4085	.85	.497	.787	.000
14.53	.4325	.90	.460	.850	.000
13.76	.4566	.95	.430	.901	.000
13.34	.4710	.98	.420	.934	.000
13.07	.4806	1.00	.418	.959	.000
12.82	.4902	1.02	.418	.986	.000
12.45	.5046	1.05	.423	1.033	.000
11.89	.5287	1.10	.442	1.125	.000
11.37	.5527	1.15	.473	1.234	.000
10.89	.5767	1.20	.509	1.354	.000
10.06	.6248	1.30	.571	1.568	.000
9.34	.6728	1.40	.561	1.610	.000
8.17	.7690	1.60	.372	1.228	.000
7.26	.8651	1.80	.214	.877	.000
6.23	1.0093	2.10	.101	.581	.000
5.23	1.2015	2.50	.071	.361	.000
4.36	1.4418	3.00	.036	.180	.000
3.27	1.9224	4.00	.073	.016	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - FULL LOAD
SPEED = 12.0 KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
56.14	.1119	.20	.023	.001	.000
37.43	.1679	.30	.054	.006	.000
28.07	.2238	.40	.102	.020	.000
22.46	.2798	.50	.176	.063	.000
18.71	.3358	.60	.295	.176	.000
16.04	.3917	.70	.481	.459	.000
14.03	.4477	.80	.652	.926	.000
13.21	.4757	.85	.679	1.121	.000
12.48	.5036	.90	.689	1.275	.000
11.82	.5316	.95	.713	1.423	.000
11.46	.5484	.98	.740	1.520	.000
11.23	.5596	1.00	.763	1.590	.000
11.01	.5708	1.02	.791	1.666	.000
10.69	.5876	1.05	.839	1.789	.000
10.21	.6156	1.10	.929	2.008	.000
9.76	.6435	1.15	1.012	2.203	.000
9.36	.6715	1.20	1.049	2.302	.000
8.64	.7275	1.30	.922	2.073	.000
8.02	.7834	1.40	.692	1.620	.000
7.02	.8954	1.60	.375	1.007	.000
6.24	1.0073	1.80	.215	.696	.000
5.35	1.1752	2.10	.101	.437	.000
4.49	1.3990	2.50	.048	.227	.000
3.74	1.6788	3.00	.050	.059	.000
2.81	2.2384	4.00	.038	.025	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - 50 PCT. FUEL
SPEED = 12.0 KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
66.39	.0946	.20	.016	.001	.000
44.26	.1420	.30	.039	.004	.000
33.20	.1893	.40	.075	.015	.000
26.56	.2366	.50	.131	.045	.000
22.13	.2839	.60	.225	.126	.000
18.97	.3312	.70	.374	.333	.000
16.60	.3786	.80	.470	.631	.000
15.62	.4022	.85	.447	.717	.000
14.75	.4259	.90	.412	.767	.000
13.98	.4495	.95	.387	.812	.000
13.55	.4637	.98	.380	.843	.000
13.28	.4732	1.00	.379	.867	.000
13.02	.4827	1.02	.380	.893	.000
12.65	.4969	1.05	.386	.936	.000
12.07	.5205	1.10	.406	1.022	.000
11.55	.5442	1.15	.437	1.125	.000
11.07	.5678	1.20	.474	1.241	.000
10.21	.6152	1.30	.546	1.474	.000
9.48	.6625	1.40	.565	1.586	.000
8.30	.7571	1.60	.403	1.291	.000
7.38	.8518	1.80	.238	.932	.000
6.32	.9937	2.10	.113	.622	.000
5.31	1.1830	2.50	.073	.394	.000
4.43	1.4196	3.00	.040	.207	.000
3.32	1.8928	4.00	.082	.009	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - BURNED OUT
SPEED = 12.0 KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
90.30	.0696	.20	.009	.000	.000
60.20	.1044	.30	.022	.003	.000
45.15	.1392	.40	.044	.011	.000
36.12	.1739	.50	.081	.034	.000
30.10	.2087	.60	.141	.096	.000
25.80	.2435	.70	.174	.182	.000
22.58	.2783	.80	.146	.219	.000
21.25	.2957	.85	.132	.230	.000
20.07	.3131	.90	.123	.243	.000
19.01	.3305	.95	.119	.257	.000
18.43	.3409	.98	.118	.268	.000
18.06	.3479	1.00	.119	.275	.000
17.71	.3549	1.02	.120	.283	.000
17.20	.3653	1.05	.122	.296	.000
16.42	.3827	1.10	.128	.321	.000
15.70	.4001	1.15	.137	.349	.000
15.05	.4175	1.20	.147	.381	.000
13.89	.4523	1.30	.174	.457	.000
12.90	.4871	1.40	.205	.553	.000
11.29	.5566	1.60	.274	.805	.000
10.03	.6262	1.80	.313	1.048	.000
8.60	.7306	2.10	.228	1.012	.000
7.22	.8697	2.50	.126	.717	.000
6.02	1.0437	3.00	.127	.493	.000
4.52	1.3916	4.00	.072	.228	.000

UNIT RESPONSES
DUAL DRAFT ICEBREAKER
STABILIZED
MODEL TEST CONDITION
SPEED = 12.0 KNOTS

PERIOD	FREQ.	OMEGA	ROLL	TANK1	TANK2
64.00	.0982	.20	.018	.001	.000
42.66	.1473	.30	.042	.004	.000
32.00	.1964	.40	.079	.015	.000
25.60	.2454	.50	.138	.045	.000
21.33	.2945	.60	.233	.126	.000
18.28	.3436	.70	.390	.337	.000
16.00	.3927	.80	.537	.705	.000
15.06	.4173	.85	.533	.839	.000
14.22	.4418	.90	.498	.916	.000
13.47	.4664	.95	.469	.975	.000
13.06	.4811	.98	.460	1.013	.000
12.80	.4909	1.00	.458	1.041	.000
12.55	.5007	1.02	.459	1.072	.000
12.19	.5154	1.05	.465	1.124	.000
11.64	.5400	1.10	.488	1.227	.000
11.13	.5645	1.15	.522	1.345	.000
10.67	.5891	1.20	.560	1.470	.000
9.85	.6382	1.30	.609	1.655	.000
9.14	.6873	1.40	.567	1.617	.000
8.00	.7854	1.60	.350	1.165	.000
7.11	.8836	1.80	.197	.824	.000
6.09	1.0309	2.10	.094	.542	.000
5.12	1.2272	2.50	.068	.330	.000
4.27	1.4727	3.00	.031	.155	.000
3.20	1.9636	4.00	.070	.021	.000

DUAL DRAFT ICEBREAKER
NO STABILIZER
EASTERN ARCTIC - FULL LOAD
SPEED = 0. KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION	SIGNIFICANT WAVE HEIGHT, FEET				
DEGREES	8.00	12.00	20.00	30.00	40.00
15	.57	1.66	3.05	3.75	4.05
30	1.10	3.20	5.88	7.23	7.82
45	1.55	4.52	8.30	10.21	11.04
60	1.88	5.51	10.13	12.46	13.49
75	2.08	6.12	11.27	13.87	15.01
90	2.15	6.34	11.67	14.37	15.55
105	2.10	6.17	11.34	13.96	15.10
120	1.91	5.58	10.24	12.60	13.63
135	1.57	4.58	8.41	10.34	11.19
150	1.12	3.25	5.97	7.34	7.93
165	.58	1.69	3.10	3.80	4.11

SHORT-CRESTED SEAS

DIRECTION	SIGNIFICANT WAVE HEIGHT, FEET				
DEGREES	8.00	12.00	20.00	30.00	40.00
0	1.09	3.19	5.86	7.21	7.80
15	1.16	3.40	6.24	7.68	8.31
30	1.33	3.90	7.17	8.82	9.55
45	1.53	4.50	8.28	10.18	11.02
60	1.71	5.03	9.25	11.39	12.32
75	1.84	5.39	9.92	12.20	13.21
90	1.88	5.52	10.16	12.50	13.52
105	1.84	5.41	9.94	12.23	13.24
120	1.72	5.06	9.30	11.44	12.38
135	1.55	4.54	8.34	10.26	11.10
150	1.35	3.94	7.24	8.91	9.63
165	1.18	3.44	6.32	7.77	8.40
180	1.11	3.24	5.94	7.30	7.90

DUAL DRAFT ICEBREAKER
NO STABILIZER
EASTERN ARCTIC - 50 PCT. FUEL
SPEED = 0. KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.16	.60	1.89	2.89	3.40
30	.30	1.13	3.59	5.50	6.48
45	.38	1.54	4.95	7.62	8.98
60	.40	1.79	5.89	9.10	10.75
75	.37	1.94	6.47	10.02	11.84
90	.38	1.98	6.64	10.28	12.16
105	.40	1.97	6.54	10.11	11.94
120	.43	1.84	6.00	9.25	10.92
135	.41	1.58	5.06	7.77	9.16
150	.31	1.16	3.68	5.63	6.63
165	.17	.62	1.94	2.96	3.48

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.0
0	.27	1.08	3.50	5.38	6.3
15	.28	1.14	3.70	5.70	6.7
30	.30	1.29	4.21	6.50	7.6
45	.33	1.47	4.83	7.45	8.8
60	.35	1.63	5.38	8.30	9.8
75	.38	1.74	5.75	8.88	10.4
90	.38	1.79	5.89	9.10	10.7
105	.38	1.75	5.78	8.92	10.5
120	.37	1.65	5.42	8.37	9.8
135	.34	1.50	4.89	7.54	8.9
150	.31	1.32	4.28	6.60	7.7
165	.29	1.17	3.78	5.81	6.8
180	.28	1.12	3.57	5.49	6.4

DUAL DRAFT ICEBREAKER
NO STABILIZER
GREAT LAKES - FULL LOAD
SPEED = 0. KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION	SIGNIFICANT WAVE HEIGHT, FEET				
DEGREES	8.00	12.00	20.00	30.00	40.00
15	.40	1.42	3.04	3.94	4.34
30	.76	2.72	5.84	7.56	8.33
45	1.05	3.80	8.18	10.60	11.67
60	1.25	4.59	9.91	12.84	14.15
75	1.36	5.06	10.96	14.22	15.67
90	1.40	5.23	11.33	14.69	16.19
105	1.38	5.10	11.04	14.31	15.77
120	1.28	4.65	10.03	12.99	14.31
135	1.08	3.86	8.31	10.75	11.84
150	.78	2.77	5.94	7.69	8.46
165	.40	1.44	3.10	4.01	4.41

SHORT-CRESTED SEAS

DIRECTION	SIGNIFICANT WAVE HEIGHT, FEET				
DEGREES	8.00	12.00	20.00	30.00	40.00
0	.74	2.68	5.78	7.49	8.25
15	.78	2.85	6.14	7.96	8.76
30	.89	3.26	7.03	9.11	10.04
45	1.02	3.75	8.10	10.50	11.56
60	1.14	4.18	9.04	11.72	12.91
75	1.22	4.48	9.68	12.55	13.83
90	1.25	4.59	9.92	12.85	14.16
105	1.22	4.49	9.71	12.58	13.86
120	1.15	4.21	9.09	11.78	12.98
135	1.04	3.78	8.16	10.58	11.65
150	.91	3.30	7.11	9.21	10.14
165	.80	2.89	6.23	8.06	8.88
180	.76	2.73	5.87	7.60	8.36

DUAL DRAFT ICEBREAKER
NO STABILIZER
GREAT LAKES - 50 PCT. FUEL
SPEED = 0. KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION	SIGNIFICANT WAVE HEIGHT, FEET				
DEGREES	8.00	12.00	20.00	30.00	40.00
15	.16	.52	1.72	2.73	3.26
30	.29	.98	3.26	5.19	6.20
45	.37	1.33	4.48	7.16	8.58
60	.38	1.53	5.32	8.54	10.25
75	.34	1.63	5.83	9.39	11.28
90	.34	1.67	5.97	9.63	11.57
105	.37	1.67	5.89	9.48	11.38
120	.41	1.58	5.42	8.69	10.41
135	.40	1.37	4.59	7.31	8.75
150	.31	1.02	3.34	5.31	6.34
165	.17	.54	1.76	2.79	3.34

SHORT-CRESTED SEAS

DIRECTION	SIGNIFICANT WAVE HEIGHT, FEET				
DEGREES	8.00	12.00	20.00	30.00	40.00
0	.26	.93	3.17	5.06	6.07
15	.27	.98	3.35	5.36	6.43
30	.28	1.10	3.81	6.10	7.32
45	.31	1.25	4.36	7.00	8.39
60	.33	1.39	4.85	7.79	9.35
75	.35	1.48	5.19	8.34	10.00
90	.36	1.52	5.31	8.54	10.25
105	.36	1.49	5.21	8.37	10.04
120	.35	1.41	4.89	7.85	9.42
135	.33	1.28	4.41	7.08	8.49
150	.30	1.13	3.87	6.20	7.43
165	.28	1.01	3.42	5.46	6.54
180	.27	.97	3.24	5.16	6.18

DUAL DRAFT ICEBREAKER
NO STABILIZER
GREAT LAKES - BURNED OUT
SPEED = 0. KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION	SIGNIFICANT WAVE HEIGHT, FEET				
DEGREES	8.00	12.00	20.00	30.00	40.00
15	.10	.17	.53	1.97	3.34
30	.18	.29	.99	3.74	6.35
45	.20	.32	1.31	5.17	8.80
60	.15	.26	1.50	6.18	10.55
75	.13	.22	1.60	6.73	11.51
90	.22	.29	1.64	6.84	11.69
105	.18	.29	1.65	6.82	11.64
120	.19	.33	1.57	6.32	10.76
135	.22	.37	1.38	5.33	9.05
150	.19	.31	1.04	3.87	6.55
165	.11	.18	.56	2.04	3.45

SHORT-CRESTED SEAS

DIRECTION	SIGNIFICANT WAVE HEIGHT, FEET				
DEGREES	8.00	12.00	20.00	30.00	40.00
0	.14	.23	.93	3.66	6.22
15	.15	.23	.98	3.87	6.58
30	.15	.24	1.09	4.40	7.49
45	.16	.25	1.24	5.03	8.58
60	.17	.27	1.37	5.60	9.56
75	.18	.28	1.46	5.99	10.23
90	.18	.29	1.50	6.14	10.48
105	.18	.30	1.48	6.03	10.28
120	.18	.29	1.40	5.66	9.66
135	.18	.29	1.28	5.11	8.71
150	.17	.27	1.14	4.49	7.64
165	.16	.26	1.02	3.97	6.75
180	.16	.26	.98	3.76	6.39

DUAL DRAFT ICEBREAKER
NO STABILIZER
MODEL TEST CONDITION
SPEED = 0. KNOTS

****** TABLE OF RMS ROLL ANGLE IN DEGREES ******

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.18	.78	2.43	3.58	4.14
30	.33	1.48	4.62	6.83	7.89
45	.43	2.04	6.39	9.46	10.95
60	.45	2.40	7.63	11.32	13.10
75	.44	2.62	8.39	12.47	14.44
90	.45	2.69	8.62	12.81	14.84
105	.47	2.65	8.47	12.57	14.56
120	.48	2.46	7.75	11.49	13.30
135	.45	2.09	6.52	9.65	11.16
150	.34	1.52	4.72	6.98	8.06
165	.18	.80	2.48	3.66	4.23

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.30	1.44	4.52	6.69	7.74
15	.31	1.52	4.78	7.09	8.20
30	.34	1.72	5.45	8.08	9.35
45	.37	1.97	6.25	9.27	10.73
60	.41	2.19	6.96	10.33	11.96
75	.43	2.34	7.45	11.05	12.80
90	.44	2.40	7.63	11.32	13.11
105	.44	2.35	7.48	11.09	12.84
120	.42	2.21	7.01	10.40	12.04
135	.39	2.00	6.32	9.37	10.84
150	.35	1.75	5.53	8.19	9.48
165	.32	1.55	4.87	7.21	8.34
180	.31	1.47	4.60	6.81	7.88

DUAL DRAFT ICEBREAKER
STABILIZED
EASTERN ARCTIC - FULL LOAD
SPEED = 0. KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.31	.62	1.07	1.40	1.60
30	.62	1.22	2.09	2.73	3.12
45	.89	1.76	3.00	3.92	4.47
60	1.11	2.20	3.74	4.87	5.55
75	1.26	2.51	4.26	5.54	6.30
90	1.33	2.66	4.52	5.86	6.65
105	1.33	2.63	4.46	5.77	6.54
120	1.21	2.40	4.06	5.25	5.94
135	.99	1.96	3.33	4.31	4.89
150	.69	1.37	2.35	3.05	3.46
165	.35	.70	1.21	1.58	1.79

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.63	1.25	2.13	2.77	3.16
15	.67	1.34	2.28	2.97	3.38
30	.78	1.56	2.65	3.45	3.93
45	.92	1.82	3.10	4.03	4.58
60	1.03	2.06	3.50	4.54	5.17
75	1.12	2.23	3.78	4.91	5.58
90	1.16	2.30	3.91	5.06	5.75
105	1.14	2.27	3.85	4.99	5.66
120	1.07	2.14	3.63	4.70	5.33
135	.97	1.92	3.27	4.23	4.80
150	.84	1.68	2.85	3.69	4.18
165	.74	1.47	2.49	3.23	3.66
180	.69	1.38	2.35	3.04	3.44

DUAL DRAFT ICEBREAKER
STABILIZED
EASTERN ARCTIC - 50 PCT. FUEL
SPEED = 0. KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.16	.30	.54	.84	1.09
30	.31	.57	1.03	1.62	2.10
45	.41	.77	1.44	2.27	2.95
60	.45	.91	1.75	2.79	3.64
75	.47	1.01	2.00	3.18	4.14
90	.52	1.11	2.18	3.42	4.42
105	.57	1.18	2.26	3.50	4.48
120	.58	1.15	2.17	3.31	4.20
135	.51	1.00	1.86	2.82	3.56
150	.38	.73	1.36	2.05	2.59
165	.20	.38	.72	1.08	1.36

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.29	.55	1.02	1.61	2.10
15	.30	.58	1.09	1.72	2.24
30	.34	.66	1.27	2.00	2.60
45	.38	.77	1.49	2.34	3.04
60	.43	.88	1.69	2.66	3.45
75	.47	.96	1.85	2.90	3.75
90	.49	1.01	1.94	3.03	3.90
105	.50	1.01	1.95	3.02	3.87
120	.48	.98	1.86	2.88	3.68
135	.45	.90	1.71	2.63	3.36
150	.41	.81	1.53	2.34	2.97
165	.37	.73	1.37	2.08	2.64
180	.35	.70	1.31	1.98	2.51

DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - FULL LOAD
SPEED = 0. KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.27	.52	.91	1.24	1.46
30	.52	1.01	1.77	2.41	2.83
45	.74	1.44	2.52	3.43	4.03
60	.90	1.77	3.12	4.25	4.99
75	1.00	2.00	3.55	4.83	5.65
90	1.07	2.14	3.78	5.13	5.99
105	1.08	2.15	3.78	5.10	5.94
120	1.01	1.99	3.49	4.70	5.46
135	.84	1.65	2.90	3.90	4.53
150	.59	1.17	2.06	2.79	3.24
165	.30	.61	1.07	1.45	1.68

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.52	1.02	1.79	2.44	2.86
15	.55	1.09	1.91	2.60	3.05
30	.64	1.26	2.22	3.02	3.54
45	.75	1.47	2.59	3.53	4.13
60	.84	1.67	2.93	3.99	4.66
75	.91	1.81	3.18	4.32	5.04
90	.94	1.87	3.29	4.47	5.21
105	.93	1.85	3.26	4.41	5.15
120	.89	1.75	3.08	4.17	4.86
135	.80	1.59	2.79	3.77	4.39
150	.71	1.40	2.45	3.31	3.85
165	.62	1.23	2.16	2.91	3.38
180	.59	1.16	2.04	2.75	3.19

DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - 50 PCT. FUEL
SPEED = 0. KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.17	.30	.51	.78	1.02
30	.31	.56	.97	1.49	1.95
45	.42	.76	1.35	2.09	2.74
60	.46	.89	1.64	2.57	3.38
75	.47	.98	1.87	2.94	3.85
90	.52	1.09	2.06	3.18	4.13
105	.57	1.16	2.15	3.28	4.22
120	.59	1.14	2.07	3.12	3.98
135	.52	1.00	1.79	2.67	3.38
150	.38	.73	1.31	1.95	2.47
165	.20	.38	.69	1.03	1.30

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.29	.54	.96	1.49	1.95
15	.30	.57	1.03	1.59	2.09
30	.34	.65	1.19	1.85	2.42
45	.39	.76	1.40	2.17	2.83
60	.44	.86	1.60	2.47	3.22
75	.47	.94	1.75	2.70	3.51
90	.50	.99	1.84	2.82	3.65
105	.50	1.00	1.85	2.82	3.64
120	.49	.96	1.77	2.70	3.47
135	.45	.89	1.64	2.47	3.17
150	.41	.80	1.46	2.20	2.81
165	.38	.73	1.32	1.97	2.51
180	.36	.69	1.25	1.87	2.38

DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - BURNED OUT
SPEED = 0. KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.11	.17	.23	.27	.31
30	.20	.30	.41	.49	.58
45	.24	.36	.53	.67	.81
60	.19	.36	.63	.85	1.05
75	.18	.42	.79	1.09	1.34
90	.29	.56	1.00	1.35	1.63
105	.33	.64	1.11	1.48	1.79
120	.36	.66	1.12	1.48	1.78
135	.35	.61	1.00	1.31	1.57
150	.27	.47	.75	.98	1.17
165	.14	.25	.40	.53	.63

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.17	.26	.39	.49	.59
15	.17	.27	.42	.54	.65
30	.18	.31	.50	.66	.80
45	.20	.36	.61	.81	.98
60	.23	.42	.72	.97	1.17
75	.26	.48	.82	1.10	1.33
90	.28	.52	.90	1.20	1.44
105	.29	.54	.93	1.24	1.49
120	.29	.54	.92	1.22	1.47
135	.28	.51	.87	1.15	1.38
150	.26	.48	.79	1.05	1.26
165	.25	.44	.73	.96	1.15
180	.24	.43	.70	.92	1.10

DUAL DRAFT ICEBREAKER
STABILIZED
MODEL TEST CONDITION
SPEED = 0. KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION	SIGNIFICANT WAVE HEIGHT, FEET				
DEGREES	8.00	12.00	20.00	30.00	40.00
15	.17	.32	.59	.91	1.17
30	.32	.60	1.13	1.75	2.25
45	.43	.83	1.57	2.46	3.16
60	.48	.98	1.92	3.02	3.89
75	.51	1.09	2.18	3.44	4.41
90	.55	1.19	2.36	3.68	4.69
105	.60	1.24	2.43	3.74	4.73
120	.60	1.21	2.31	3.51	4.42
135	.53	1.04	1.98	2.98	3.74
150	.39	.76	1.44	2.17	2.71
165	.20	.40	.76	1.14	1.42

SHORT-CRESTED SEAS

DIRECTION	SIGNIFICANT WAVE HEIGHT, FEET				
DEGREES	8.00	12.00	20.00	30.00	40.00
0	.30	.59	1.12	1.75	2.25
15	.32	.62	1.19	1.87	2.40
30	.36	.71	1.38	2.17	2.78
45	.41	.83	1.62	2.53	3.24
60	.46	.94	1.84	2.87	3.67
75	.50	1.03	2.01	3.12	3.98
90	.52	1.07	2.10	3.25	4.13
105	.52	1.07	2.09	3.23	4.10
120	.50	1.03	2.00	3.07	3.89
135	.47	.95	1.83	2.81	3.54
150	.42	.85	1.63	2.49	3.13
165	.38	.77	1.46	2.21	2.77
180	.37	.73	1.39	2.10	2.63

DUAL DRAFT ICEBREAKER
NO STABILIZER
EASTERN ARCTIC - FULL LOAD
SPEED = 12.0 KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.05	.22	.97	1.68	2.07
30	.11	.48	1.83	3.04	3.71
45	.19	.94	3.07	4.75	5.63
60	.35	1.67	4.95	7.25	8.39
75	.76	2.91	6.71	9.01	10.12
90	1.65	4.66	8.68	10.84	11.84
105	3.49	7.11	10.86	12.66	13.47
120	6.88	10.24	12.99	14.22	14.77
135	6.51	8.06	9.36	10.02	10.35
150	1.93	2.76	3.63	4.16	4.46
165	.77	1.16	1.60	1.89	2.06

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.18	.80	2.40	3.63	4.27
15	.28	1.04	2.77	4.06	4.72
30	.57	1.65	3.71	5.14	5.86
45	1.17	2.60	4.98	6.54	7.33
60	1.98	3.74	6.35	7.99	8.81
75	2.80	4.82	7.56	9.22	10.03
90	3.47	5.66	8.42	10.02	10.80
105	3.94	6.18	8.82	10.30	11.01
120	4.16	6.33	8.73	10.03	10.65
135	4.11	6.09	8.16	9.24	9.76
150	3.88	5.57	7.25	8.10	8.51
165	3.62	5.03	6.34	7.00	7.32
180	3.52	4.80	5.95	6.53	6.81

DUAL DRAFT ICEBREAKER
NO STABILIZER
EASTERN ARCTIC - 50 PCT. FUEL
SPEED = 12.0 KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.02	.04	.29	.72	1.03
30	.04	.09	.70	1.70	2.40
45	.05	.16	1.18	2.79	3.86
60	.06	.31	1.76	3.62	4.82
75	.14	.74	3.57	6.36	7.94
90	.38	1.61	5.17	8.09	9.66
105	1.15	3.54	8.31	11.47	13.02
120	3.32	7.46	12.97	15.93	17.27
135	8.48	13.56	18.30	20.45	21.38
150	8.88	11.82	14.21	15.27	15.75
165	2.29	3.31	4.30	4.82	5.07

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.04	.16	.96	2.04	2.76
15	.06	.26	1.22	2.41	3.17
30	.15	.56	1.92	3.35	4.23
45	.44	1.20	3.06	4.77	5.77
60	1.18	2.42	4.76	6.67	7.75
75	2.23	3.99	6.77	8.82	9.94
90	3.31	5.54	8.67	10.80	11.92
105	4.21	6.80	10.16	12.28	13.36
120	4.86	7.66	11.06	13.09	14.09
135	5.28	8.14	11.41	13.25	14.14
150	5.58	8.40	11.41	13.03	13.78
165	5.78	8.55	11.33	12.74	13.39
180	5.85	8.60	11.29	12.62	13.22

DUAL DRAFT ICEBREAKER
NO STABILIZER
GREAT LAKES - FULL LOAD
SPEED = 12.0 KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.04	.16	.79	1.42	1.79
30	.08	.37	1.80	3.19	3.95
45	.13	.61	2.50	4.26	5.23
60	.23	1.17	3.82	5.89	6.98
75	.48	2.04	5.53	7.96	9.17
90	1.16	3.82	8.11	10.60	11.78
105	2.77	6.31	10.48	12.60	13.57
120	6.40	10.44	14.00	15.61	16.32
135	11.28	13.77	15.64	16.47	16.84
150	2.69	3.77	4.85	5.46	5.79
165	1.04	1.54	2.08	2.41	2.60

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.12	.56	1.98	3.24	3.93
15	.19	.75	2.32	3.64	4.35
30	.41	1.29	3.19	4.66	5.43
45	.96	2.22	4.48	6.09	6.93
60	2.00	3.57	6.07	7.77	8.64
75	3.16	5.03	7.69	9.40	10.27
90	4.18	6.29	9.01	10.67	11.50
105	4.94	7.18	9.85	11.41	12.17
120	5.38	7.62	10.13	11.52	12.19
135	5.48	7.60	9.83	11.01	11.58
150	5.36	7.26	9.14	10.09	10.55
165	5.24	6.91	8.46	9.21	9.57
180	5.19	6.77	8.17	8.85	9.17

DUAL DRAFT ICEBREAKER
NO STABILIZER
GREAT LAKES - 50 PCT. FUEL
SPEED = 12.0 KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.02	.04	.23	.59	.87
30	.04	.08	.57	1.42	2.03
45	.05	.14	1.09	2.62	3.65
60	.06	.26	1.59	3.44	4.67
75	.12	.65	3.21	5.83	7.35
90	.35	1.45	4.89	7.87	9.51
105	1.11	3.39	8.34	11.73	13.41
120	3.19	7.19	12.86	16.00	17.45
135	8.32	13.68	18.91	21.32	22.36
150	10.80	14.33	17.14	18.37	18.90
165	2.70	3.89	5.01	5.58	5.85

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.04	.14	.86	1.87	2.55
15	.06	.23	1.11	2.23	2.96
30	.15	.51	1.80	3.17	4.03
45	.42	1.14	2.95	4.62	5.62
60	1.15	2.35	4.68	6.60	7.70
75	2.28	4.03	6.83	8.91	10.06
90	3.49	5.74	8.93	11.11	12.27
105	4.52	7.17	10.62	12.81	13.94
120	5.28	8.18	11.71	13.82	14.87
135	5.82	8.81	12.23	14.18	15.11
150	6.24	9.23	12.42	14.14	14.95
165	6.52	9.49	12.48	14.00	14.70
180	6.62	9.58	12.50	13.94	14.58

DUAL DRAFT ICEBREAKER
NO STABILIZER
GREAT LAKES - BURNED OUT
SPEED = 12.0 KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.03	.06	.13	.24	.37
30	.06	.12	.25	.43	.66
45	.10	.20	.37	.58	.92
60	.16	.27	.43	.72	1.30
75	.24	.33	.52	1.42	2.55
90	.23	.33	1.08	3.47	5.78
105	.46	.88	2.72	6.22	9.16
120	1.51	2.49	6.01	11.35	15.05
135	3.08	4.95	10.06	15.67	19.09
150	5.19	7.74	13.31	18.16	20.82
165	4.96	7.25	11.09	13.85	15.24

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.08	.14	.26	.46	.76
15	.09	.16	.29	.62	1.05
30	.12	.21	.47	1.13	1.83
45	.23	.38	.95	2.12	3.18
60	.49	.80	1.87	3.65	5.12
75	.97	1.53	3.22	5.64	7.49
90	1.59	2.46	4.81	7.80	9.96
105	2.21	3.37	6.29	9.74	12.11
120	2.76	4.18	7.54	11.26	13.73
135	3.25	4.89	8.57	12.40	14.85
150	3.66	5.47	9.40	13.24	15.60
165	3.93	5.86	9.94	13.77	16.04
180	4.02	5.99	10.13	13.95	16.19

DUAL DRAFT ICEBREAKER
NO STABILIZER
MODEL TEST CONDITION
SPEED = 12.0 KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION	SIGNIFICANT WAVE HEIGHT, FEET				
DEGREES	8.00	12.00	20.00	30.00	40.00
15	.02	.05	.37	.91	1.28
30	.04	.11	.81	1.94	2.70
45	.05	.19	1.20	2.69	3.68
60	.06	.39	2.06	3.96	5.14
75	.15	.83	3.74	6.53	8.08
90	.43	1.91	5.87	8.86	10.39
105	1.27	3.99	8.89	11.94	13.40
120	3.53	7.70	12.90	15.60	16.81
135	8.99	13.75	17.96	19.83	20.63
150	7.00	9.36	11.34	12.26	12.69
165	1.94	2.82	3.69	4.15	4.39

SHORT-CRESTED SEAS

DIRECTION	SIGNIFICANT WAVE HEIGHT, FEET				
DEGREES	8.00	12.00	20.00	30.00	40.00
0	.04	.19	1.06	2.16	2.87
15	.07	.31	1.34	2.55	3.30
30	.17	.65	2.10	3.54	4.41
45	.47	1.32	3.29	4.99	5.97
60	1.26	2.55	4.96	6.86	7.92
75	2.28	4.06	6.87	8.90	9.99
90	3.26	5.49	8.61	10.69	11.77
105	4.07	6.62	9.91	11.97	13.00
120	4.62	7.35	10.64	12.58	13.54
135	4.94	7.68	10.80	12.55	13.39
150	5.12	7.78	10.62	12.12	12.83
165	5.24	7.82	10.38	11.67	12.26
180	5.29	7.82	10.28	11.49	12.03

DUAL DRAFT ICEBREAKER
STABILIZED
EASTERN ARCTIC - FULL LOAD
SPEED = 12.0 KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.06	.19	.49	.78	.97
30	.13	.41	1.03	1.59	1.96
45	.23	.70	1.64	2.46	3.00
60	.41	1.11	2.37	3.40	4.07
75	.72	1.69	3.23	4.42	5.17
90	1.29	2.53	4.26	5.53	6.30
105	2.21	3.61	5.38	6.60	7.32
120	3.26	4.61	6.22	7.28	7.89
135	2.92	4.19	5.62	6.51	7.01
150	2.14	3.09	4.12	4.74	5.09
165	1.00	1.48	2.02	2.35	2.53

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.20	.55	1.22	1.80	2.18
15	.26	.66	1.39	2.01	2.41
30	.45	.96	1.84	2.55	3.01
45	.75	1.40	2.45	3.28	3.80
60	1.13	1.93	3.13	4.05	4.63
75	1.51	2.44	3.77	4.76	5.38
90	1.84	2.88	4.28	5.31	5.93
105	2.07	3.17	4.59	5.60	6.20
120	2.19	3.28	4.67	5.62	6.18
135	2.19	3.24	4.52	5.38	5.88
150	2.10	3.08	4.23	4.98	5.41
165	2.01	2.91	3.95	4.61	4.98
180	1.97	2.84	3.83	4.45	4.80

DUAL DRAFT ICEBREAKER
STABILIZED
EASTERN ARCTIC - 50 PCT. FUEL
SPEED = 12.0 KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.02	.05	.14	.24	.34
30	.04	.11	.30	.52	.73
45	.06	.20	.53	.90	1.24
60	.11	.34	.85	1.43	1.96
75	.24	.63	1.37	2.20	2.93
90	.55	1.14	2.18	3.32	4.24
105	1.22	2.04	3.42	4.86	5.93
120	2.24	3.27	4.99	6.63	7.72
135	2.62	3.95	6.04	7.68	8.66
150	3.04	4.51	6.42	7.70	8.41
165	2.20	3.21	4.34	5.02	5.37

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.06	.17	.42	.71	.97
15	.09	.23	.52	.86	1.16
30	.19	.40	.80	1.26	1.65
45	.39	.69	1.25	1.87	2.38
60	.68	1.10	1.87	2.66	3.28
75	1.03	1.61	2.59	3.56	4.28
90	1.39	2.13	3.33	4.44	5.23
105	1.71	2.59	3.95	5.16	5.99
120	1.95	2.93	4.40	5.64	6.46
135	2.12	3.16	4.68	5.90	6.68
150	2.23	3.32	4.84	6.01	6.73
165	2.30	3.41	4.93	6.05	6.72
180	2.33	3.45	4.96	6.05	6.70

DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - FULL LOAD
SPEED = 12.0 KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION	SIGNIFICANT WAVE HEIGHT, FEET				
DEGREES	8.00	12.00	20.00	30.00	40.00
15	.05	.14	.37	.59	.76
30	.10	.30	.76	1.21	1.54
45	.18	.52	1.23	1.91	2.40
60	.31	.84	1.83	2.74	3.38
75	.56	1.32	2.60	3.71	4.46
90	1.05	2.07	3.61	4.88	5.70
105	1.95	3.17	4.87	6.17	6.98
120	3.05	4.36	6.08	7.31	8.03
135	3.01	4.41	6.10	7.19	7.79
150	2.76	3.95	5.23	5.99	6.41
165	1.34	1.98	2.67	3.07	3.29

SHORT-CRESTED SEAS

DIRECTION	SIGNIFICANT WAVE HEIGHT, FEET				
DEGREES	8.00	12.00	20.00	30.00	40.00
0	.15	.41	.93	1.42	1.77
15	.21	.51	1.09	1.62	1.99
30	.37	.77	1.48	2.12	2.56
45	.64	1.18	2.06	2.82	3.34
60	1.01	1.68	2.74	3.62	4.21
75	1.40	2.22	3.44	4.42	5.05
90	1.76	2.71	4.05	5.09	5.75
105	2.03	3.08	4.49	5.54	6.19
120	2.20	3.28	4.70	5.72	6.34
135	2.26	3.34	4.70	5.65	6.21
150	2.25	3.29	4.56	5.42	5.91
165	2.21	3.22	4.41	5.18	5.62
180	2.20	3.19	4.34	5.08	5.50

DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - 50 PCT. FUEL
SPEED = 12.0 KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.02	.05	.13	.22	.30
30	.04	.10	.28	.47	.64
45	.06	.19	.49	.81	1.11
60	.10	.33	.80	1.30	1.77
75	.24	.61	1.30	2.05	2.73
90	.55	1.12	2.08	3.12	4.00
105	1.24	2.03	3.30	4.68	5.76
120	2.28	3.25	4.85	6.44	7.55
135	2.59	3.84	5.85	7.53	8.58
150	2.96	4.37	6.28	7.63	8.39
165	2.22	3.22	4.39	5.12	5.52

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.06	.16	.39	.64	.87
15	.09	.22	.49	.79	1.06
30	.19	.39	.76	1.17	1.54
45	.40	.68	1.20	1.77	2.25
60	.68	1.09	1.80	2.54	3.15
75	1.03	1.58	2.50	3.43	4.14
90	1.39	2.09	3.23	4.31	5.10
105	1.70	2.54	3.84	5.03	5.87
120	1.94	2.87	4.29	5.53	6.37
135	2.10	3.11	4.58	5.81	6.62
150	2.22	3.26	4.75	5.94	6.70
165	2.28	3.35	4.84	5.99	6.70
180	2.30	3.38	4.87	6.01	6.70

DUAL DRAFT ICEBREAKER
STABILIZED
GREAT LAKES - BURNED OUT
SPEED = 12.0 KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.03	.05	.11	.21	.30
30	.05	.09	.23	.42	.58
45	.08	.15	.36	.63	.84
60	.12	.24	.52	.83	1.05
75	.20	.38	.74	1.07	1.30
90	.33	.63	1.11	1.49	1.79
105	.80	1.25	1.84	2.34	2.84
120	1.70	2.28	3.00	3.70	4.43
135	1.99	2.71	3.67	4.63	5.57
150	2.16	2.91	3.92	4.90	5.79
165	1.80	2.29	2.93	3.53	4.06

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.06	.12	.27	.45	.60
15	.08	.15	.32	.51	.66
30	.14	.24	.45	.67	.84
45	.28	.43	.70	.96	1.18
60	.49	.72	1.06	1.39	1.69
75	.75	1.06	1.50	1.92	2.32
90	1.02	1.42	1.96	2.48	2.98
105	1.26	1.73	2.36	2.97	3.55
120	1.45	1.97	2.66	3.33	3.96
135	1.59	2.13	2.86	3.57	4.23
150	1.68	2.24	3.00	3.72	4.40
165	1.74	2.31	3.07	3.81	4.50
180	1.76	2.33	3.10	3.84	4.53

DUAL DRAFT ICEBREAKER
STABILIZED
MODEL TEST CONDITION
SPEED = 12.0 KNOTS

**** TABLE OF RMS ROLL ANGLE IN DEGREES ****

LONG-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
15	.02	.06	.17	.29	.40
30	.05	.13	.36	.62	.86
45	.07	.23	.60	1.04	1.43
60	.12	.39	.96	1.61	2.19
75	.26	.68	1.50	2.41	3.16
90	.58	1.21	2.33	3.54	4.47
105	1.23	2.10	3.55	5.01	6.04
120	2.26	3.32	5.09	6.67	7.69
135	2.65	4.02	6.07	7.61	8.50
150	3.08	4.53	6.33	7.49	8.12
165	2.10	3.06	4.10	4.71	5.03

SHORT-CRESTED SEAS

DIRECTION DEGREES	SIGNIFICANT WAVE HEIGHT, FEET 8.00	12.00	20.00	30.00	40.00
0	.07	.19	.48	.80	1.10
15	.10	.25	.58	.96	1.29
30	.20	.43	.87	1.37	1.79
45	.40	.72	1.33	1.99	2.52
60	.69	1.14	1.95	2.78	3.40
75	1.04	1.65	2.67	3.66	4.37
90	1.40	2.17	3.40	4.50	5.27
105	1.72	2.62	4.00	5.18	5.98
120	1.96	2.95	4.42	5.62	6.40
135	2.12	3.17	4.67	5.84	6.57
150	2.23	3.32	4.80	5.90	6.57
165	2.30	3.40	4.86	5.91	6.52
180	2.32	3.43	4.88	5.90	6.49

APPENDIX E

"Operator's Manual for the
Anti-Roll Stabilizer on the
United States Coast Guard
Dual Draft Icebreaker"

Ship Research Incorporated Report CG80-4
July 1981

OPERATOR'S MANUAL

for the
Antiroll Stabilizer
on the
United States Coast Guard
Dual Draft Icebreaker

Report Number CG80-4
July 31, 1981

Prepared for

Davidson Laboratory
Stevens Institute of Technology
Hoboken, New Jersey

I. IMPORTANT NOTES

****READ THIS MANUAL CAREFULLY BEFORE USING STABILIZER ****

General Operation

Do not use the stabilizer if the corrected GM would be less than the minimum allowable.

Fill the tank to a water level of 9'6" above the 01 level. To do this, simply fill the tank until water starts to discharge from the outlet of the overflow line.

Emergency Procedures

If the ship is in danger of capsizing due to inadequate static stability, then drain the tank by opening the dump valves. The valves may be operated remotely from the bridge, or they can be operated manually.

II. PRINCIPLES OF OPERATION

The stabilizer tank installed on this ship is the passive, U-Tube type. The stabilizer consists of a pair of wing tanks, port and starboard, connected at the bottom by a crossover duct. The water in one wing tank can flow easily into the other wing tank through this crossover. The tops of the wing tanks are also connected by a large air crossover pipe to allow air to flow between the two tanks. A vent is located on the air crossover pipe.

When the ship rolls, the water in the stabilizer "sloshes" from side to side in much the same way as coffee in a cup does when one walks with it. This sloshing in turn causes moments on the ship which, with a properly designed tank, reduce the roll motion of the ship. The operation of the tank can best be understood in terms of the energy flow in the system. The waves impart energy to the ship causing it to roll. Since the ship has very little roll resistance this energy causes the roll of an unstabilized ship to build up until the ship has a large enough motion to dissipate as much energy as the waves are imparting to the ship. This usually leads to quite large roll motions. If the stabilizing tank is operating, and if the tank has a slosh period near the roll resonant period, a significant portion ofthe roll energy is transferred to the tank. This energy is exhibited as the slosh motions of the tank. If the tank has sufficient damping of its own, then most of this energy is converted to heat. Thus, the tank drains much of the roll energy away from the ship, thereby preventing excessive roll motion of the ship. The amount of energy transformed into heat is, however, not so great as to cause large increases in the temperature of the water. When the following instructions are followed carefully, the tank installed in this ship will have near optimum period and damping for excellent stabilization.

Even in exceptionally severe storm seas it is practically impossible for the sloshing motion in the tank to be large enough to cause water to impact the tank top. This phenomenon is called tank saturation. These impacts, if they occur at all, will be heard in the neighborhood of the tank or felt at the tops of the stabilizer wing tanks. As long as the impacts are relatively infrequent, there is little likelihood of damage to the tank and little degradation of the tank's performance. If the impacts are frequent, however, it is advisable to drain the tank a small amount to reduce the occurrence of the impact.

III. DESCRIPTION OF THE SYSTEM

The antiroll system consists of a single tank and its associated hardware. The tank is located between frames 127-143. The bottom of the tank is at the 01 level.

The antiroll tank consists of two wing tanks and a cross-over duct. The wing tanks are each 16 feet long, 10 feet wide, and 22 feet high. The crossover duct extends across the ship to connect the bottom of the wing tanks. The duct is just under the ______________________________ room.

An air crossover pipe connects the tops of the wing tanks. To provide for flow of air between the wing tanks, an 18 inch diameter air crossover pipe has been provided. This pipe runs just over the top of the house, above the generator room, at about frame 140.

There is a vent in the air crossover pipe at about the ship centerline. This vent serves the entire tank.

The tank is equipped with a fill and drain connection, located ____________________ (Location of fill connection) ________. There is a manual valve between the connection and the tank. The connection is a __________ (type and size of fill connection).

The tank has an overflow system to assure proper water level in the tank. The discharge of the overflow line is ______ (location of overflow line discharge) ________. The overflow line is equipped with a valve, normally closed, located ______ (location of overflow line valve) ________. When the overflow line valve is open and the stabilizer is too full, water will flow out the discharge of the overflow line. The overflow line is vented. The vent is (location of overflow line vent) ______ . This vent is an essential component of the overflow system.

The tank is equipped with an emergency dumping system. Four six-inch drain lines run from the bottom corners of the tank to points on the main deck in the exterior passageway below the tank where they discharge over the side. There is a valve in each line located inside the house just under the 01 deck. These valves are located ______________________________ (locations of the dump valves) . The valves may be manually operated, if necessary, but are intended to be operated remotely from the bridge. A control box for the valves is located on the bridge. A switch is provided to open and close each valve. Indicator lights show which valves are open. The emergency dumping system can drain the tank in eight to ten minutes if all four valves are opened.

IV. OPERATING PROCEDURES

In order to assure safe and efficient operation of the roll stabilization system, the following procedures should be strictly adhered to.

Static Stability Considerations

The stabilizer free surface must be considered when computing the ship's GM. When filled to the design level, the stabilizer contains 4390 cubic feet of fluid. The weight of the fluid is

$$W = 122.3\ \gamma \qquad \text{(long tons)}$$

where γ is the specific gravity of the fluid in the stabilizer. If the fluid is fresh water, then $\gamma = 1.0$. If the fluid is sea water, then $\gamma = 1.026$. The center of gravity of the fluid is 54.25 feet above the keel. The stabilizer also has a free surface loss which reduces the GM. The moment of inertia of the free surface is 170,000 feet^4. The loss in GM due to the free surface is

$$GM_{loss} = 4737\ \gamma / \Delta \qquad \text{(feet)}$$

where Δ is the total ship displacement in long tons including the fluid in the stabilizer. For example, if the fluid in the stabilizer is sea water and the total ship displacement is 6000 tons, then the GM loss due to the free surface is 4737 x 1.026/ 6000 = 0.81 feet.

Under normal operating circumstances the GM with the stabilizer operating is sufficient. The stabilizer should be used unless an unusual loading condition reduces the GM below the minimum allowable.

Filling the Stabilizer

Use the following procedure:

1. Check both the vent on the air crossover pipe and the overflow line vent.
2. Open the valve on the overflow line.
3. Assure that all the dump valves are closed by checking the indicator lights on the control box. If not, then close them.
4. Connect the fill hose to the fill line fitting and open the fill line valve.
5. Pump water into the stabilizer.
6. If the stabilizer is to be protected with antifreeze, then stop pumping water when the desired amount of water has entered the tank. The desired amount can be calculated from the following formula:

$$\text{Gallons of water} = 328 \times \textit{percent water by volume}$$

For example, if the fluid is to be 40 percent antifreeze and 60 percent water, then the gallons of water is 328 x 40 = 13,120 gallons. Then pump the antifreeze into the tank.

7. At the first sign of water out of the overflow line, stop filling the tank.
8. Close the fill line valve and disconnect the fill line.
9. Close the overflow line valve.

Draining the Stabilizer

Under ordinary circumstances it will not be necessary to drain the stabilizer. On those occasions when it is necessary, use the following procedure:

1. Check the vent on the air crossover pipe.
2. The stabilizer may be drained by opening one or more dump valves, <u>if there are no reasons not to do so.</u> Reasons

not to use the dump valves include, but are not limited to:

- the water contains expensive antifreeze
- the water has somehow become contaminated
- the water may cascade onto workers or equipment below the dump valves

See the next paragraph for dumping procedure. If the dump valves cannot be used, then the tank must be drained through the fill line, as follows:

3. Connect the drain hose to the fill line, and open the fill line valve.
4. Pump the water from the tank.
5. Close the fill line valve and disconnect the drain hose.

Emergency Procedures

If an emergency arises in which it appears that the safety of the ship is in grave jeopardy, the stabilizer may be drained to maximize the ship's static stability. When the stabilizer is drained the rolling motions may increase, but the chances of capsizing will probably decrease.

1. If time and conditions permit, check the vent on the air crossover pipe.
2. Open the dump valves by operating the switches in the control box on the bridge.
3. Check to see that water is draining out the dump lines. If not, open the dump valves manually.

Maintenance

The stabilizer should be given normal maintenance one would give to large tanks aboard ship. When possible, inspect the tank for excessive corrosion. It is extremely important to repair or replace any loose structure, and to remove any loose gear. Inspect the vent on the air crossover pipe for free operation regularly; particularly guard against freezing in cold weather. When possible, check that the overflow line and the overlow vent line are clear.

V. SUMMARY

The stabilization system has been designed for carefree operation throughout the life of the ship. It is very important, however, that both the operating procedures presented here and normal safety precautions be closely adhered to.

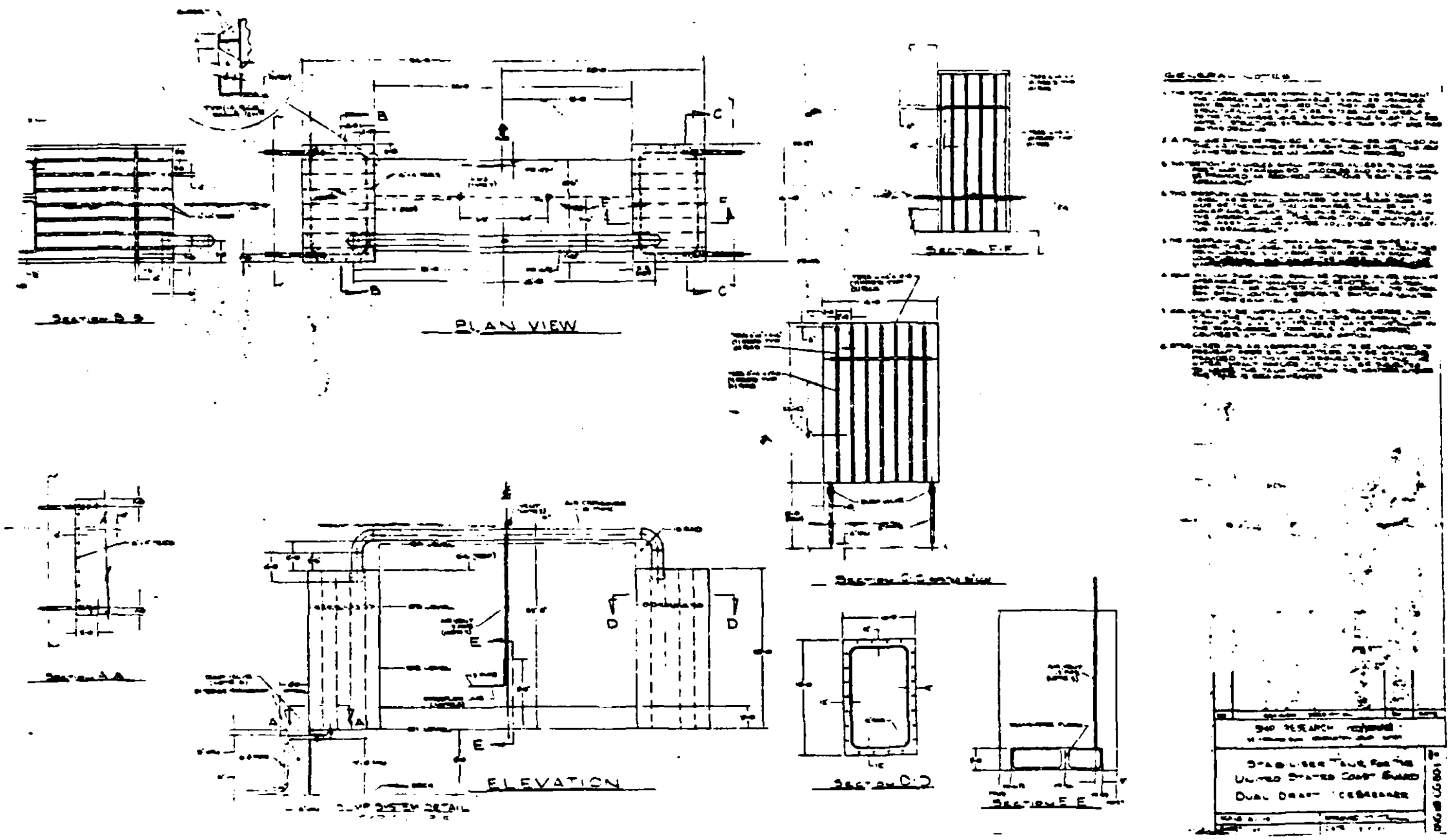
APPENDIX F

Reduced Scale Final Design Drawing

"Stabilizer Tank for the United States Coast Guard"

Ship Research Incorporated Drawing CG80-1

August 1981



GENERAL NOTES
SECTION B-B
PLAN VIEW
SECTION F-F
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SECTION D-D
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SHIP RESEARCH
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UNITED STATES COAST GUARD
DUAL DRAFT ICEBREAKER
DWG UG 801

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